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MORPHODYNAMICS IN THE LAGOS LAGOON: OBSERVATION AND INFERENCES OF CHANGE

by

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Faculty of Science and Engineering

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Morphodynamics in the Lagos Lagoon: observation and inferences of change

Alfred Sunday Alademomi

Abstract

The focus of this research is the study of lagoon ecosystem interaction and adjustment of the lagoon floor morphologies, water dynamics and sequences of change involving the motion of sediment. The aim of the study is to implement a functional mechanism to evaluate and analyse changes in the Lagos Lagoon and its ecosystem, with the objectives: (i) to investigate the extent and impact of urban expansion on the Lagoon coastline and its ecosystem; (ii) to quantify changes in the spatial extent of mangroves by use of satellite images from 1984 to 2016; (iii) to investigate the spatial dynamics of the Lagoon water floor and estimate its flushing time, (iv) to investigate the behaviour and relationship pattern of the Lagoon hydrodynamic parameters;, (v) to collect sediment samples from the Lagoon, analyse their settling behaviour and particle size distribution (PSD) in order to study their spatial evolution and characterisation; and (vi) to initiate a model that can predict the influence of sea level rise on the Lagoon ecosystem. The existing problem of an overcrowded human population in Lagos, the incessant repository of industrial effluence into its Lagoon, and increased flooding from the immediate watershed generate the research questions for this thesis. Lack of studies in the areas of morphodynamics and hydrodynamics on the Lagoon is a gap in the body of coastal knowledge, especially the temporal and long term dynamics of a significant Lagoon like that of Lagos. Understanding the dynamics of the Lagoon will enhance efficient monitoring, sustainable management and hence reveal the great importance the Lagoon preserves for the coastal region.

Landsat images (1984 – 2016) of the study area (Lagos Lagoon) and its ecosystem were obtained for some specific data derivations. Land Surface Temperature (LST), NDVI and delineated Lagoon coastline were derived from the images. An Environment for

Visualizing Images (ENVI) and a Geographic Information System (GIS) were used to extract land classification information, likewise, the GIS was used to develop a model for investigating the Lagoon coastline changes. With the use of ENVI and GIS software, land classification types were derived with the percentage of the coverage area for each land use classification for the years of study. A novel empirical method was designed to collect in-situ hydrodynamic data for both the dry and wet seasons in 2014, this was correlated and analysed using a case study approach. Also, in-situ bathymetric data was collected in 2014 to join the 2008 available data for studying the changes in the Lagoon water bed morphology. Functional models were used to examine the interaction of the various hydrodynamic information that was studied on the Lagoon.

Results and inferences from the study show that the wetland of the system is depleting rapidly with increase urbanisation. In both lateral and vertical directions, the morphological shape of the Lagoon is reducing both in size and depth. The result from the model that investigated the system coastline indicates that reclamation and recession are taking place on the Lagoon coast at an approximate ratio of 4 to 1 whereas, the total surface area has reduced to approximately 204.51km^2 as opposed to its approximate area of 208km^2 as at the year 2010. The results from the analysis of the Lagoon salinity implies a wide salinity variation between the dry and the wet season; this confirms the system as brackish water in the dry season and freshwater in the wet season. Other inferences reveal the critical point of well-mixed water mass, significant vertical mixing during the wet season and a stable state during the dry season. In overview, the ratio of the Lagoon stratification during the dry season to that of the wet season is approximately 1 to 7 and flushing time of approximately 26 days and 22 days respectively. Lastly, the Lagoon possesses a varying settling velocity that is uniquely related to the diameter of its particles at various spatial locations. This research has been able to provide baseline investigations concerning the morphology and hydrodynamic study of the Lagos Lagoon.

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Nomenclatures

ACPC = Atmospheric Correction Parameter Calculator

ANOVA = Analysis of Variance

ASSETS = Assessment of Estuarine Trophic Status

ASTER = Advanced Spaceborne Thermal Emission and Reflection

BP = Before Present

BT = Brightness Temperature

CDU = Control Display Unit

CO_2 = Carbondioxide

CTD = Coductivity Temperature and Depth

CVI = Coastal Vulnerability Index

DOM = Dissolved Organic Matter

EMR = Electromagnetic Radiation

ENVI = Environment for Visualising Images

ETM = Enhance Thematic Mapper

GIS = Geographic Information System

GOS = Global Obersving System

GPS = Global Positioning System

GRACE Follow-on = Gravity Revoery And Climate Experiment Follow-on

H_2O = Water

HH = High High

HL = High Low

HW = High Water

IDW = Inverse Distance Weighting

IPCC = Intergovernmental Plan on Climate Change

LGA = Local Government Area

LH =Low High

LL = Low Low

LCO = Lagos Coastal Observatory

LOICZ = Land-Ocean Interactions in the Coastal Zone

LSD = Least Significant Difference

LSE = Land Surface Emissivity

LST = Land Surface Temperature

LUCC Land Use and land Cover Change

LUT = Look Up table

LW = Low Water

MATLAB = Matrix Laboratory

MSS = Multispectral Scanner

N_2O = Nitrous Oxide

NDVI = Normalised Difference Vegetable Index

O_2 = Oxygen

O_3 = Ozone

Ppt = Part per thousand

PSD = Particle Size Distribution

RGB = Red Green Blue

SD = Significant Difference

SLC = Scan-Line Corrector

SLR = Sea Level Rise

SMART = Specific Measurable Attainable Relevant and Timely

SWIR = Short Wave Infrared

TAR = Third Assessment Report

TIR = Thermal Infrared

TIN = Triangular Irregular Network

TIR = Thermal Infrared

TM = Thematic Mapper

ToA = Top of Atmosphere

T-S = Temperature – Salinity

UKHO = United Kingdom Hydrographic Office

Unilag = University of Lagos

URV = Ultraviolet Radiations

USGS = United States Geological Survey

VHI = Vegetation Health Index

VNIR = Visible Near Infrared

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There is no existence without the existence of GOD, the creator of ALL things "For in Him (GOD) we live, and move, and have our being; as certain also of your own poets has said, for we are also his offspring (product of His existence)" – Acts 17:28. GOD has a divine life in me that cannot exist but through Him and this life can only and had only be maintained by GOD the giver (Andrew Murray). Thus GOD has given and maintained my life ever since my existence hence, I am greatly indebted to GOD for all He has endowed in me (my PhD inclusive) and made manifest one after the other as He has designed them in the scope of time and space. "Now unto the King eternal, immortal, invisible, the only wise GOD, be honour and glory forever and ever (Amen)" – 1 Timothy 1:17.

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Author’s Declaration

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Relevant scientific seminars, workshops and conferences were regularly attended at which part of the research were often presented; external institutions were visited for consultation and training purposes, and papers prepared for publications. A list of oral and poster presentations, workshops and conferences attended are outlined below:

Oral Presentations

- Alfred Sunday Alademomi, Victor Abbott & Andrew Manning. 2013 – Oral presentation on the background and literature review of the PhD study at Geomatics research group, University of Plymouth, United Kingdom.
- Alfred Sunday Alademomi, Victor Abbott & Andrew Manning (2013). Coastal Lagoons. A seminar presentation in partial fulfilment of the requirement for General Teaching Associates (GTA) Course, Plymouth University Plymouth, UK , 16th May 2013.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Lagos Lagoon coastline and morphology changes induced by post-industrial expansion in Lagos Nigeria. ECSA 54 at Sesimbra, Portugal 12 – 16 may 2014.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Oral presentation of the research introduction, literature review, methodology and data collection, at Holly Room, Kestrel, HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, United Kingdom. 14th July 2014.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Measuring and Monitoring the Spatial and Temporal Dynamic of Coastal Lagoon Sea-bed Growth. Postgraduate Society Conference, Plymouth University, 20th June 2016.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Coastal Lagoon Ecosystem Reduction Associated with Urban Growth and its Spatio-particle Characterisation. Centre for Marine and Coastal Policy Research (MarCoPol) autumn 2016 seminar series, Plymouth University, 4th October 2016.

Poster Presentations

- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Making Waves 2015: Marine and Maritime Conference for Ph.D students and Early Career Researchers, 12th February 2015. Plymouth Marine Laboratory, Matters Centre, Plymouth United Kingdom.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Land use land cover and morphological changes within and around a coastal lagoon: A case study of Lagos Lagoon, Nigeria. Poster presentation at 3rd Marine and Coastal policy conference, 27 – 28 October 2015, Brest France
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Assessing salt intrusion in Lagos lagoon: planning, observation and analysis. The 8th MMU postgraduate Research Conference, Manchester Metropolitan University, Manchester UK, 5th November 2015.
- Alfred Sunday Alademomi, Victor Abbott, Andrew Manning & Richard Whitehouse. Spatial variability and coastal lagoon ecosystem reduction associated with urban growth Postgraduate Society Conference, Plymouth University, 20th June 2016.

Conferences attended

- Making Waves 2012: Marine and Maritime Conference for Ph.D students and Early Career Researchers, November 2012. Plymouth Marine Laboratory, Matters Centre, Plymouth United Kingdom
- Young Coastal Scientists and Engineers Conference, 25th-26th March 2013 held at University of Aberdeen, Scotland United Kingdom.
- Annual Marine Institute Research Centre Conference, at Plymouth Lecture Theatre, Portland Square Building, Plymouth University, on the 4th June 2013.

- Making Waves 2013: Marine and Maritime Conference for Ph.D students and Early Career Researchers, 28th November 2013. Plymouth Marine Laboratory, Matters Centre, Plymouth United Kingdom.

- Estuarine & Coastal Sciences Association (ECSA) 54- Coastal System under change: tuning assessment and management tools 12 – 16 may 2014 Sesimbra, Portugal.

- 2nd Marine and Coastal Policy Forum (MarCoPol) Conference, 18-20 June 2014, Plymouth, United Kingdom.

- 16th Biennial Challenger Society Marine Science 2014 Conference, Plymouth University, 8-11 September 2014.

- Making Waves 2015: Marine and Maritime Conference for Ph.D students and Early Career Researchers, 12th February 2015. Plymouth Marine Laboratory, Matters Centre, Plymouth United Kingdom.

- 3rd Marine and Coastal Policy Forum (MarCoPol) Conference, 27 – 28 October 2015, Brest, France

- The 8th MMU postgraduate Research Conference, Manchester Metropolitan University, Manchester UK, 5th November 2015.

Workshops/Training attended

- Research Methods Field Course, at University of Highlands and Islands (Scottish Association for Marine Science), Oban Scotland, United Kingdom, from 3rd-10th April, 2013.

- Skill training in boat driving at Plymouth Powerboat School Limited, Royal Yachting Association, Plymouth, United Kingdom, 28-29 May 2013

- Swimming training at Plymouth Life Centre, Plymouth, every Wednesday in June and July 2013.
- Developing R skills for Spatial Analysis and Visualization, 6th January, 2014. Foster Court, University London, United Kingdom.
- Introduction to GIS – Using ArcGIS (Vector Applications), 16th – 17th January, 2014. Room G. 19, School of Geography, University of Leeds, United Kingdom.

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Signed……………………………………

Date – 12th January 2017

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Introduction

The coastal environment has been faced with various enormous challenges throughout the world over time due to increased human pressure and the down-slide still continues (Adger *et al.*, 2005; Folke, 2006). It is a matter of great concern as this induces incessant changes on its morphodynamics, hydrodynamics and geomorphological structure which in turn affects the natural wellbeing of the environment and its features as well as the health of its inhabitants. However, there is a need for each coastal scientist to focus on a specific aspect of the problem confronting the coast to ensure a rigorous impactful research on the coast because of its global significance. Such is the investigation that is focused in this research, the morphodynamic study in the Lagos Lagoon: observation and inferences of change. This chapter gives an overview perspective of the research that enclose some details about the coastal zone the home of coastal lagoons, the associated interactions that exist between the morphological and the hydrodynamic characterisation of lagoons. Lagos Lagoon as a case study has its uniqueness in terms of morphodynamic pattern as a result of the factors and processes influencing the changes in it. This chapter considered the rationale and statement of the research problem, which informed the aim and various objectives that are set to achieve the research plan.

The coastal zone is one key area across the world that draws attention from a large percentage of the population of the world. This statement is supported by the definition of Artioli *et al.* (2005) who define coastal zones as areas of the highest environmental pressure. Also, the coastal zone or region can briefly be described as that space in which terrestrial environments influence marine environments and vice versa (Carter, 1995).

Bird (2008) agreed in principle with Carter's definition when in his book he defined the coastal zone "as a region of varying width, including the shore and the nearshore zone, out at least to the line where waves break, and extending in-land to the limit of penetration of marine influences: the crest of a cliff, the head of a tidal estuary, or the rising ground behind coastal low-lands, or dunes, lagoons and swamps" (Bird, 2008). To appropriately delineate the coastal zone for integrated management purpose, Balaguer *et al*, (2008) defined the coastal zones to be "regions that constitute extreme high variability in diverse nature and generally possess high socio-ecological/socio-economic values". From the highlights of the coastal zones definitions, it could be inferred that the pressure on the coastal zones come largely from increased human population concentration on the zone. This statement embraces the assertion that "about two thirds of the world population live in coastal areas and drive a high pressure on the environment with the production of wastes (solid, liquid and gaseous) and exploitation of natural resources" (Artioli *et al.,* 2005). A schematic example of the coastal environment represented in profile and plan is shown in Figure 1.1.

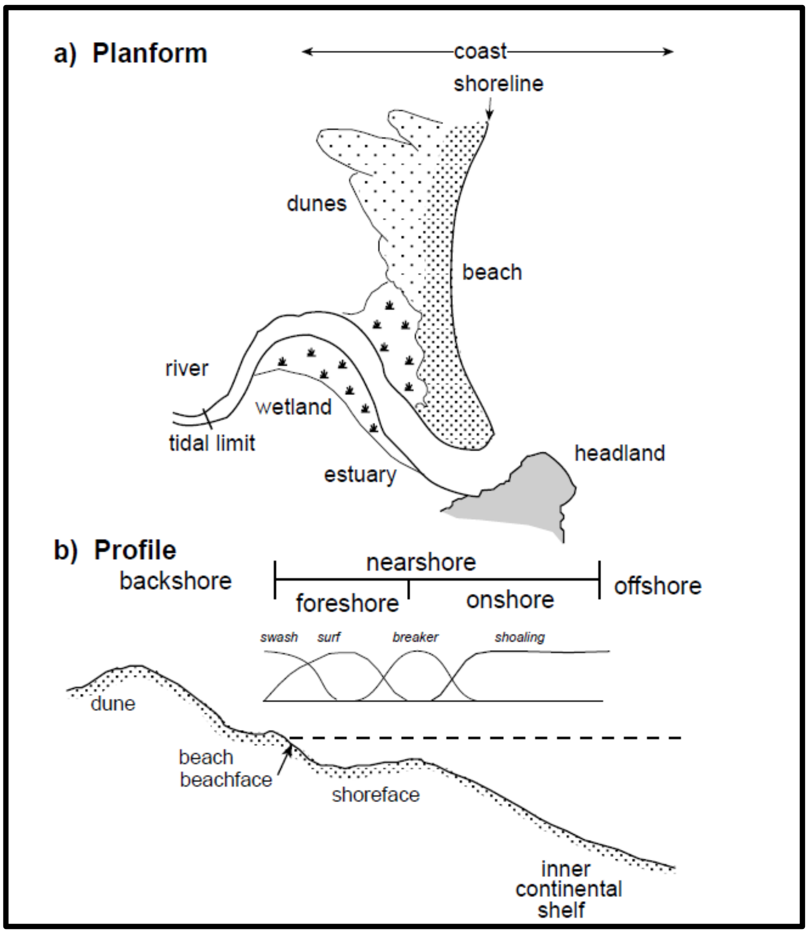


Figure 1.1: A schematic diagram of coastal embayment in (a) plan and (b) profile. It shows some of the key landforms based on proximity to the shore, wave characteristics and substrate (base material) as undertaken by Woodroffe (2002)

There are different interesting landforms (among which are the lagoon, estuary, dune, barrier reef, beach, bay cliff, coral reef, wetlands, and muddy shorelines) in the coastal regions due to variations in geological composition of different environments and the changing climate from one geographical zone to the other (Woodroffe, 2002). This research focuses on one of the prominent coastal landforms 'the coastal lagoon' and especially one in Nigeria, popularly known as 'the Lagos Lagoon'.

Coastal lagoons are common landforms of the world's low lying coastal plains that are formed on coastal plains which are gently sloping seaward and where there is an abundance of sand (Phleger, 1981). They are widespread all over the world, being shallow aquatic ecosystems that develop at the interface between coastal terrestrial and marine ecosystems (Gonenc & Wolflin, 2004). They play a major role in the coastal dynamic equilibrium for the exchange of materials between land and sea. Consequent upon this, wetlands which function as a medium of water quality improvement, biological productivity and flood risk reduction, always co-exist parallel with lagoons (Mitsch & Gosselink, 2000). Due to the nearness of lagoons to wetlands and morphological characteristic which allows for their restricted exchange of water with the adjacent ocean, they are generally vulnerable to organic processes which occur as a direct impact of increasing population densities along the coastline (Lloret *et al*., 2008; Newton *et al*., 2003).

In addition, coastal lagoons that are considered as one of the most fragile marine environments could likely be altered by global environmental climate change (Lloret *et al.*, 2008). Such effects may include loss of wetlands due to, sea level surface temperature rise, sea level rise, and change in hydrodynamics of water masses, alteration in water salinity and increased dissolved oxygen.

However, the rise in sea level or global environmental change normally produces a morphological response in the coastal area that drowns many river-valley systems. These, if eventually isolated by longshore current barriers, form lagoons of complex outline (Barnes, 1980). The rapidly induced changes in the morphological and hydrodynamic nature of coastal lagoons due to an incessant increase in population around the coast is prominently brought into display around the Lagos Lagoon (Figure 1.2), the study area in this research thesis. This is the major force that propels this investigation of the morphological and hydrodynamic changes in the Lagos Lagoon.

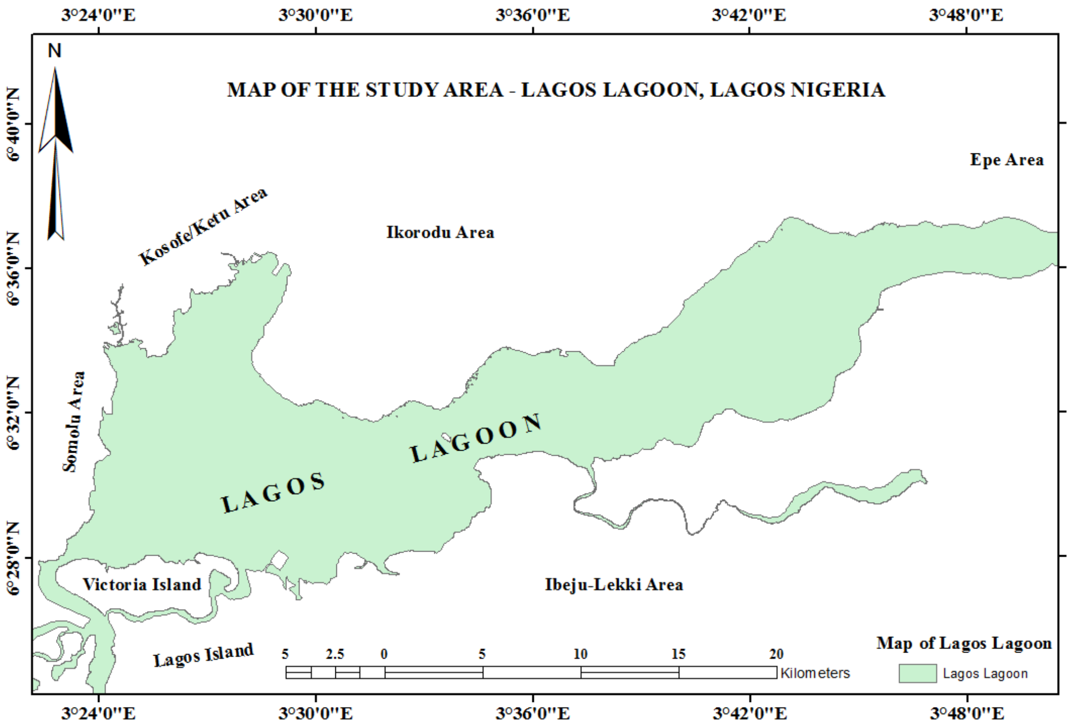


Figure 1.2: Map showing the study area (Lagos Lagoon) with different settlement areas around it

1.2 Background of the study

It is necessary to have a good understanding of the coast and coastal lagoon interaction. Such comprehensive understanding will help to gain proper knowledge of what constitutes the coastal lagoons and limits of their existence along the coastal regions of the world.

1.2.1 The Coast

The coast is appealing but very challenging to study as a result of the various dynamic processes acting upon it. This may be the reason why Haslett (2009) wrote that:

"… the coast is a very special environment in that it is where the land, sea and atmosphere meet. Each of these contributes to the workings of the coast, making coasts very interesting, and yet challenging subjects to study."

Haslett continues that the coast is:

"… the location of major human settlements and human activities which can have significant impacts on the operation of the coasts to the point of environmental and socio-economic degradation. The study of the coasts, therefore, is highly interdisciplinary, incorporating geology, physical and human geography, oceanography, climatology, sociology, economics, engineering, planning, and management, and so on. It is perhaps one of the best examples of interdisciplinary environmental science."

The coastal zone as defined by Rochette (2009) includes,

"… the coastal waters (including the land therein and thereunder) and the adjacent shorelands (including the waters therein and thereunder), strongly influenced by each and in proximity to the shorelines of the several coastal states, and includes islands transitional and intertidal areas, saltmarshes, wetlands and beaches."

From this picture, it is possible to realign the definition of the coast as the landed area in the coastal zone that is affected by its closeness to the sea. Hinrichsen (1997) put it this way - that the coast is that part of the land most affected by its proximity to the sea and that part of the sea most affected by its closeness to the land. Recent studies have shown that the overwhelming large and growing proportion of the population is concentrated along or near the coast regions (Creel, 2003) on just 10% of the Earth's land surface (Hinrichsen, 1997). Kummu *et al,* (2011) established that over 50% of the world population lives closer than 3km to surface freshwater. Creel (2003) observed that approximately 3 billion people, about half of the world population, live within 200 kilometres of the coastline. This has led to environmental declination in the global coastal zone. The coast as an environment with a complex nature and a difficult place to manage, involving a natural system which is ever changing and is inhabited by a relentlessly growing and increasingly demanding human society (Crooks & Turner, 1999).

According to the classification done by Connolly *et al*, (2001), the coastal areas are impacted by factors which include pressure as a result of fast coastal development and coastal intensive agriculture bringing about pollution in lagoons, rivers, estuaries and lakes, and reduced coastal water quality. In addition, other factors include coastal erosion and flooding, tourism and recreational use; all these threaten the coastal zones as areas of high ecological and resource values. So many problems have associated themselves with the coastal zone since the beginning of the global industrial revolution, such as loss of habitats, continuous spread of contaminated sediments, pollution through domestic and industrial wastage, over-fishing, and direct discharge of urban wastewater.

The consequence of human impacts along with global climate change have continuously and consistently brought the coastal environment under pressure (Cummins *et al.,* 2004), and this has led to adverse environmental effects. As a way of minimising coastal impacts, there is an urgent need to protect the coastal environment; the need to strategies management goal for coastal community based human resources (Alcala, 1998), campaign for initiatives for its maintenance and restoration (Thom *et al*., 2005) and improvement of qualities of coastal ecosystems and their associated human habitat (Olsen, 2003).

1.3 Coastal lagoons and their associated morphological and hydrodynamic changes

Coastal lagoons according to Kjerfve & Magill (1989) are landforms along the margins of most continents. They are shallow water systems formed in a marginal depression behind barriers (Oliveira *et al*., 2006) and connected to the sea by one or more entrances and with little freshwater influence. Lagoons generally have restricted connections to the ocean (Kjerfve & Magill, 1989) compared to their surface area, and hence the water body is poorly flushed. This makes them exhibit long residence times in contrast to a flowing river. The degree of human activities and increased coastal urbanisation, and the impact of natural phenomena (like biological processes, physical processes, erosion, tide and wave propagation) will affect the level of morphological and hydrodynamic changes that will be experienced in any coastal lagoon.

1.3.1 Morphological change in coastal lagoons

Lagoons are sensitive areas that play a vital role among the coastal zone ecosystems as they provide suitable breeding areas for many species. In terms of formation, lagoons are formed with their long axes parallel to the coastline (Barnes, 1989; Barnes, 1980) where offshore barriers developed more or less parallel to the original shoreline. Nonetheless, the interaction of various coastal processes (Pari *et al*., 2008) and increased human action are the major forces controlling the lagoon morphology (da Silva & Duck, 2001; Duck & da Silva, 2012; Lopes *et al*., 2013) leading to gradual or rapid changes in the landscape of the coastal lagoons. Such morphology can be viewed in two dimensions, lateral or horizontal and vertical or bathymetric.

1.3.2 Hydrodynamic change in the coastal lagoons

The global characteristic depth of a lagoon as a shallow sub-coastal system makes it to be considered as vertically homogeneous (Lopes *et al.*, 2013). The hydrodynamics of any coastal lagoon continuously adapt to changes in the forcing agents like tide, wind, wave action, water exchange with the ocean, and freshwater input (Kjerfve & Magill, 1989). The level of hydrodynamic change in any lagoon is a function of the degree of impact of the various forcing agents which affect the hydrodynamic structure of such lagoon. To thoroughly investigate and assess lagoon hydrodynamics, there is a need for planning both short and long term studies to get a clear perspective of the trends that impact most significantly on the system's water dynamics. This research focuses on short and medium terms hydrodynamic changes because of the time limit for the research. Short term in this research is reckoned as changes in the Lagoon within few days and months, while medium term is reckoned with as changes within a century. The two are small compared to a geological evolution.

1.4 Rationale for the research

No coastal lagoon and its immediate catchment area remain static over any timescale (short or long). The natural balance of the coastal lagoon can be seen as the sustainability of the natural ecosystem between the sea and the coastal lagoon. However, no matter how carefully managed the natural balance; it will be susceptible to change. As a result of the general morphological features, lagoons are naturally very sensitive to dynamic balance in all aspects (Mohanty & Panda, 2009).

From the experience of living next to the Lagos Lagoon, it has been clearly observed that there are various pressures inflicting threats upon the Lagoon. Lagos' population is currently about 17 million, up from 2 to 3 million in the 1970s. Despite this pressure, research to date on the Lagoon only identifies ecological studies (Amaeze *et al.,* 2012; Edokpayi & Ayorinde, 2005; Nkwoji, Onyema & Igbo, 2010; Phillips Olusegun, Falana Adenike & Olayiwola Moshood, 2012), lagoon sensitivity and pollution studies (Amaeze *et al.*, 2012; Amaeze et al., 2015; Nkwoji *et al*., 2010), fishery and plankton sustainability (Ajagbe *et al.,* 2012; Olapoju & Edokpayi, 2014) and partial pressures on the Lagoon ecosystem habitat. All these, although, are part the outcome of the impact created by the growing population (about 17 million) of the city of Lagos Nigeria around the Lagos Lagoon. However, to the best of the author's knowledge no specific study, despite the high pressure on the Lagoon and its ecosystem, has been undertaken on the Lagoon's morphological and hydrodynamic changes.

The thesis details (i) a review of coastal lagoons, (ii) the broadening of personal skills for marine environmental science, and (iii) the synthesis and modelling within the context of coastal lagoons in relation to its hydrodynamics and morphological structure. The above rationales coupled with the concern about the impact of the increasing population living around the Lagos Lagoon, have formed the basis for researching into this topic.

1.5 Statement of the research problem

The sensitive natural balance of the Lagos Lagoon and its catchment has no doubt changed mainly because of increased urbanisation and industrial expansion in Lagos Nigeria from the mid-1970s. The growth brought about (i) the discharge of effluent from all industries combined with discharges from urban runoffs into the Lagoon, and (ii) an increase in human activities around the Lagoon coastline and also inside the Lagoon. These must have affected and changed the natural landscape and behaviour of the Lagoon.

To investigate this problem, there will be a review of the contributory factors to both the Lagoon's hydrodynamics and the morphological changes of the system within the catchment area. Among such factors are (i) changes in the Lagoon's coastline as a result of reclamation, erosion and coastline retreat, and (ii) variability in temperature, salinity, surface velocity, the Lagoon mixing/stratification. The investigation into these factors is necessary since the physical, biological and chemical variability results from the combination of these effects and their interaction. For a future study, a long-term multidisciplinary investigation of the Lagoon must be considered which should include the physio-chemical, biogeochemical, hydrological and biological parameters. Howbeit, this research is limited to an investigation into the effect of some physical variability and the consequential effects on the Lagoon. The physical variability is not considered in geological or other long-term timescales but in the short-term. This means that changes in the Lagoon over a long timescale of about hundred years to thousands of years are not the concern of this study but there is a focus on changes within the range of about twenty to fifty years due to human activities since post-industrial expansion in Lagos. Consequent upon this, a general research question is generated on which the research aim is focused.

1.6 Research Aim and Objectives

The coastlines and the adjacent lagoons of the Nigerian coast have suffered several losses mainly as a result of an inability to manage the sensitive natural balance of the Lagoon and its catchment area and retain the initial ecosystem structure and forces that control the natural processes within and around the Lagoon's morphological regime. Due to increased urbanisation and industrial expansion witnessed in Lagos from the mid-1970s until the present, the Lagos Lagoon must have been seriously affected, with no remedial action in place. Hence, this study investigates morphological evolution and hydrodynamic changes in the Lagoon.

The aim of the study is therefore summarized as follows: to implement a functional mechanism to evaluate and analyse changes in the Lagos Lagoon and its catchment area.

The various objectives to achieve the aim are:

1. to investigate the extent and impact of urban expansion on the Lagoon coastline and its ecosystem;
2. to quantify changes in the spatial extent of mangroves by use of satellite images from 1984 to 2016;
3. to investigate the spatial dynamics of the Lagoon water floor and estimate its flushing time;
4. to investigate the behaviour and relationship pattern of the Lagoon hydrodynamic parameters;
5. to collect sediment samples from the Lagos Lagoon and analyse their settling behaviour and particle size distribution (PSD) in order to study their spatial evolution and characterisation;
6. to initiate a model that can predict the influence of sea level rise on the Lagoon ecosystem.

1.7 Main Research Question

The existing problem of an overcrowded human population in Lagos, the incessant repository of industrial effluence into its Lagoon, and increased flooding issues from the immediate watershed has generated two primary research questions for this thesis. They are:

- What is the spatial and temporal variability of coastal urban expansion impact on the Lagoon ecosystem?
- Are there significant spatio-temporal hydrodynamic changes that have been impacted on the Lagoon as the urban growth increases?

In most cases, the research objectives will have hypothetical questions that each of the objectives will answer in order to achieve the overall goal of the research. These questions will inform the various objectives of the research and in turn give direction to the type of analysis to be done.

1.8 Overview of the research structure

In overview, the research starts with this introduction and gives a brief overview of the coastal zone with the landforms that dominate such regions globally; among such landforms are coastal lagoons one of which is the focus of this study, on the coast of the Western part of Africa.

Chapter 2 gives the review of morphological and hydrodynamic changes in lagoon systems. The first aspect to be reviewed in chapter 2 is on coasts and coastal inlets along with estuaries; this section provides an acknowledgement of coastal inlets and the similarities and differences that exist between coastal lagoons and estuaries. It discusses coastal lagoons, their definition, origin and the size of lagoons in a global context. The chapter also reviews the common global features of lagoons and the morphology and dynamics associated with them over different timescales. Following this is a review of the coastal lagoons classifications based on some basic classification parameters. However, the impact of incessant population growth along the coastal zone and its resultant implication on coastal lagoons is also reviewed; this aspect considered the review of remote sensing methods in studying changes in the coastal area because of its proficiency and cost effectiveness. The chapter concludes with the overview of effects of climate change on the coastal lagoons and their response to Sea Level Rise (SLR).

Chapter 3 reports in detail the explanation of the different approaches to the research methodology. The methodology is in three stages. The first stage details the preliminary study which involved data requirements, data availability, data limitations, and system and equipment familiarisation and preliminary data acquisition. Stage two presents the procedure for data collection design, application and modelling. These were employed in estimating the morphological and hydrodynamic changes in the Lagoon system. Two types of data, visible thermal infrared satellite (Landsat) and field data were employed for the research analysis. The processing of the satellite data was carried out using standard software for spatial analysis and data processing (ArcGIS and MATLAB). The major problem with the optical satellite data used in the study is cloud cover. MATLAB scripts were written for the processing of satellite data to get the results on radiance, surface reflectance, brightness temperature and Land Surface Temperature (LST). Also MATLAB scripts were written to apply the models use to a hydrodynamic investigation on the Lagoon. For the Landsat data used, the method of dark pixel atmospheric correction was used for the reflective bands, while an atmospheric correction parameter calculator was employed to derive the atmospheric correction parameters for their single thermal band (band 6). A novel concept was initiated on Morris equation of rate sediment accumulation on the coastal ecosystem to generate a model that can predict influence of sea level rise on the Lagoon. Models were also developed in the ArcGIS environment to investigate changes along the Lagoon coastline and for ascertaining the system stratification pattern. Stratification and flushing time were also computed under this section. The chapter concludes with stage three, which reflects on possible long term study and demonstration of transferability.

Chapter 4 covers the mapping of spatial variabilities in the Lagoon ecosystem, a qualitative analysis of the detection of changes in the system through Landsat reflective bands signatures, qualitative analysis of changes with the use of ArcGIS, and spatial variation and characterisation of Land Surface temperature (LST) and Normalised Difference Vegetable Index (NDVI) in the ecosystem. The chapter reveals the degree of impact of depletion as a result of increased urbanisation, while linear regression analysis shows a high correlation between population growth, mangrove, swamp and built-up areas. This was also shown with the analysis of correlation between the LST and NDVI. The result of the changes along the Lagoon coastline shows that its surface area is reducing. The chapter ends with conclusion.

Chapter 5 analyses the changes on the Lagoon water bed resulting from the impact of urbanisation and the changes experienced along its coastline. The chapter performs different statistical tests and analyses on the spatial difference in the Lagoon depth characterisation. Moreover, a volume analysis was performed. It enhances the study to calculate erosion and accretion which was also depicted in map format. Lastly, the significance of the accretion variation with factors that account for uncertainty in the lagoon bottom dynamics was discussed and the Chapter ends with concluding remarks.

Chapter 6 presents a synthesis of the results of the processes of field and Landsat data that were used in the study. It discusses major findings, and assessment of salinity, temperature and stratification variability in the Lagoon. Furthermore, an assessment of spatio particle characteristics of the Lagoon is considered using two empirical functional approaches (Andreasen pipette experiment for verifying particle size distribution and Hindered experiment for determination of settling velocity). Lastly this chapter gives detailed results of the mathematical model developed for the assessment of lagoon marsh development.

Chapter 7 is the general discussions and findings of the research thesis. A comparison of the various research findings were made with the literature so as to reflect, contradict or extend previous related studies. The comparison with other literature is necessary in order to support all the deductions or inferences arising from this research. New areas for further research are recommended to support decision making and the sustainable management of coastal lagoons.

Chapter 8 reports on general conclusions that highlight the achievements of the study, the various contributions to the body of knowledge in this area of research are stressed and finally recommendations are made which can support accomplishment of further research that are highlighted in Chapter 7.

1.9 Summary

Chapter one gives a general introduction about the research, a brief overview of the coastal zone with the landforms that dominate such regions globally; among such landforms are coastal lagoons the focus of this study, along the coast of the western part of Africa. The chapter discussed the statement of the research problem, rationale for the study, the research aim and objectives, main research question and the overview of the research structure.

1.10 Conclusion

Many studies (Ajao, 1996; Ajao & Fagade, 1990b; Ajao & Fagade, 1990a; Ayoola & Kuton, 2009; Balogun, Ladigbolu & Ariyo, 2010; Don-Pedro *et al.,* 2004; Emmanuel & Onyema, 2007; Nkwoji *et al.,* 2010a; Nkwoji *et al.,* 2012; Nkwoji *et al.,* 2010b; Olatunji & Abimbola, 2010; Olowu *et al.,* 2010; Oyedele & Momoh, 2009) have been carried out on the Lagos Lagoon but the issue of morphological change and hydrodynamics have been left unaddressed. Therefore this research has found it useful and necessary to investigate this gap that has been left unattended. This leads to chapter two where a review of the various literature used in the research are summarized.

CHAPTER TWO - REVIEW OF THE STATE OF ART OF MORPHOLOGICAL AND HYDRODYNAMIC CHANGES IN LAGOON SYSTEMS

2.1 Introduction

Chapter two is a review of the studies and concepts with structure for theories in studying and assessing the morphodynamics in the Lagos Lagoon: observation and inferences of change. It presents a comprehensive review of the current understanding of key concepts underpinning this thesis, specifically the concepts of coastal inlet systems, a distinction between coastal lagoons and estuaries, the Lagoons' origin and dynamics, global lagoons' common features and classifications, the description of its hydrodynamics and morphological changes and the dynamic characterisation of its sediment. The review of literature covers extensive studies that relate to lagoon investigations and relevant work of other coastal scientists which show understanding, interpretation and analysis, clarity of thoughts, synthesis, and development of argument. Hence, the end result of the various reviewed literature helps to identify a gap within the body of coastal lagoon knowledge that this research attempts to address. Even though the study deals with a lagoon that is localised within a Nigerian context, the processes under review are generally accepted as being driven by almost the same physical principles as the larger scale outflows on the wider world coastal systems. Hence, this chapter contains a literature review that captures both the Lagos Lagoon scenario and the global lagoon concept. This chapter provides a review on coastal morphology and hydrodynamics to support what was carried out in this research. It equally provides supplement and support for the various literatures in the field.

Sections 2.2 – 2.3 provide an appreciation of the features of the coastal lagoons (Carter, 1995); and then examine the Lagoon's coverage area and the changes that occur over time.

2.2 Coastal Inlets Systems

The complex coastal systems of the world have different features, some of them look so similar that it is difficult to easily distinguish between them; such is the case of coastal lagoons and the estuaries. It is very important to study the various features of the coast so as to align the effect or influence each of the coastal landforms produces with the various geographic locations, for example bay (Swanage Isle of Purbeck, UK); cove (Lulworth Dorset, UK); cliff (Biarritz, France); estuary (Salcombe, UK). A comprehensive and in depth study of estuaries and lagoons are needed for a proper clarification of their features. Coastal lagoons are similar to estuaries in many ways, yet lagoons differ significantly from estuaries in that they are shallow inland marine waters, usually oriented parallel to the coast, generally they are wave dominated system and having depths that seldom exceed a few metres (Kjerfve, 1986). Kjerfve's definition is aligned with a structured set of lagoons from across the world, Table 2.1.

2.2.1 Estuaries

Lagoons, estuaries and deltas are the major conduit through which terrestrial materials, especially sediments, are transported and deposited in the ocean. However, Kjerfve (1994a) and Hart (2007) indicated that they are distinctly different from each other mainly by the dominant process agents of waves, tides, and fluvial discharge. Hence, the most convenient and best way to differentiate these coastal systems is that coastal lagoons are formed mainly in a wave-dominated environment, estuaries by tidal cycles while deltas by fluvial processes. See Figure 2.1 for a better pictorial representation of the systems. The understanding of these systems (lagoons, estuaries and deltas): their hydrodynamic, morphologic and sediment regimes study are therefore very critical to the future sustainability of our coast. Lagoons and estuaries are often more confused than with any other coastal landform because of their close similarities in nature, yet a slight difference exists between them in terms of entrance width to the sea. For this reason, studies about estuaries (Dyer, 1997; Prandle, 2009) will be considered in this section.

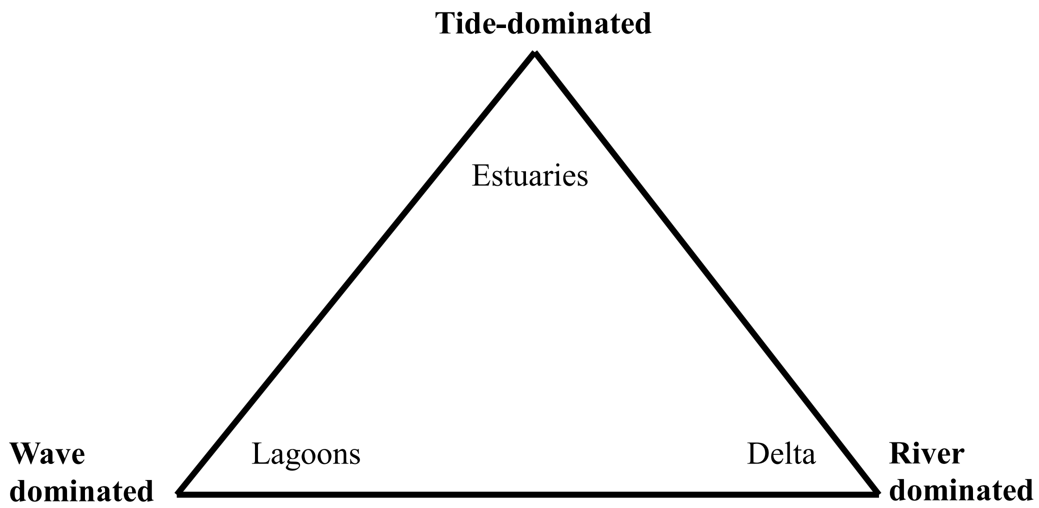


Figure 2.1: River mouth classification according to the dominant agents of waves, tides and rivers. Sourced from Hart (2007)

Deducing from the representation made in Figure 2.1, estuaries can therefore be defined as a feature peculiar mainly to coastal plain and inland river valleys, where the system is formed due to the effect of sea transgressing on the lower course of river valleys, hence containing saline water and freshwater from drainages and rivers from upland. They are influenced by tides and are usually shallow - typically less than 20 m deep (Kjerfve & Magill, 1989). This defining feature, although derived some years after the work of Pritchard (1952) and Pritchard (1967), is found to be consistent over time; hence, it is widely and generally accepted by scientists. As correctly reasoned, estuaries are complex coastal landforms; hence Pethick (1993) argued, based on this fact as quoted by Mikhailov *et al*. (2012) that it is very difficult to pin down a specific or basic definition for the estuaries. Perillo (1995) found there were analyses of over 40 scientific definitions of estuaries of which none fulfil the basic criteria (coastal bodies, border control, freshwater input, tidal action, connection with adjacent sea and characteristics of the estuary habitat) necessary to establish the existence of an estuary. However, in a concise form Dyer (1997) defined an estuary as a “semi-enclosed coastal body of water which has free and wide connection to the open sea, extending into the river as far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage”. The clarity of Dyer’s definition is scientifically acceptable with other definitions such as Pritchard (1952), Pritchard (1967) and Kjerfve & Magill (1989), and correlated in terms of shape, size and dominant agent. Despite the confusion in estuaries definition, Prichard’s approach gained wide scientific recognition (Elliott & McLusky, 2002). Mikhailov *et al*. (2012), because of the author’s ability to integrate and embrace what goes on in large coastal ecosystem regions and the ecological interaction within a large variety of water objects of the coastal zone.

2.2.2 New Definition Approach to Estuary

To combine the idea of an estuary formation into the science of river mouths and water interchange from fresh water to salt water at the region of the coast, hence, Pritchard’s definition needs refinement, in order to remove the phrase “coastal” and substitute for a “water body” for a system of water connection with the sea, as is typical in the arid region and some tropical zones of the world (Mikhailov *et al.*, 2012; Potter *et al.* 2010), this is required in order to include lagoons in the classification scheme. This idea supports the proposal of Day (1981) as cited by Mikhailov *et al.* (2012) where they point out the regular connection of an estuary with the sea, as another feature that characterises both lagoons and estuaries either in the arid, temperate and tropic regions.

In order to define an estuary exclusively different from the lagoon, consideration must be given to the extent of the inner and outer limits of the system (Elliott & McLusky, 2002). In line with this, Mikhailov *et al.* (2012) proposed a new comprehensive definition that an estuary is "an visible-enclosed system of water bodies within a river mouth area, which periodically comes into contact with the sea, hence, as a result of the effect of occasional mixing of fresh and salt water a barrier zone with water salinity varying from 1-8‰ exist at least one season in a year." This definition brings together the essential characteristics of both the inner and outer features of estuaries and as well give consideration to what happens in all regions of the world. Therefore, the above definition is all encompassing and can be more widely accepted by scientists.

The simplest way of identifying an estuary is by giving consideration to its physiographical definition (Prandle, 2009) that is the overall shape of the system. With focus on the shape of estuaries, Pethick (1993) attempted a definition of "natural" estuarine shape with focus on the mouth width, tidal length and tidal prism and he concluded that a natural estuary could be recognised by the ratio of its mouth width to both tidal length and tidal prism. He argued in his point that if for any reason this ratio is distorted through human activities by construction and reclamation, a coastal regression will occur and that will reduce the system's mouth, in that case the estuary does not function as it should, thus leading to problems of flooding, erosion and storm-surge effects. This is a major occurrence in coastal systems that are immediately adjacent to coastal cities where there is rapid increase in urbanisation and industrialisation. In simpler terms, an estuary can be distinctively defined geographically as the area of water body between a river and a coastline break. Unfortunately, many estuaries have a gradual change in shape contrary to the assumption of consistent shape as assumed by Pethick (1993), thus producing a more gradual transition between river, estuary, coastal embayment and open coast. Furthermore, the importance of topography in defining the shape of an estuary, most notably the mouth, is illustrated by Dyer (1996) who uses both the coastline form and the underwater topography or morphology, together with the associated sediment distribution to indicate the outer limit of the Severn Estuary in the United Kingdom. It is not always the case all across the coastal zone that an estuary will have its outer region dominated by tidal energy, and thus with strong tidal currents, but the inner region controlled by river currents, the usual phenomena has been that an estuary is tidal dominated. As such, the mouth will have an underwater morphology that is characterized by a series of linear banks aligned with the dominant tidal flow (Elliott & McLusky, 2002).

However, a lagoon in any of the coastal region is slightly characterised differently from an estuary, hence section 2.3 is devoted to discussion on coastal lagoons.

Table 2. 1: Global selected lagoons and their physical features (Kjerfve, 1986)

Lagoon	Country	Entrance Type	Ocean Entrance	Surface Area (km^2)	Mean Depth (m)	Length (km)	Predominant salinity Characteristics
Patos	Brazil	Choked	1	10,100	5	290	Fresh/Brackish
Mississippi	USA	Leaky	Many	2,130	3		Estuary
Coronian	Lithuania			1,600	4		
Ebrie	Ivory Coast		1	520	5	120	Fresh/Brackish
Venice	Italy			500	1.5	50	
Lagos	Nigeria	Choked	1	460	3-10	60	Fresh/Brackish
Aby	Ivory Coast		1	424	4	30	
Keta	Ghana		1	330		29	
St. Lucia	S/Africa	Choked	1	312	1		Estuary
Lekki	Nigeria		1	247	2-6	37	Fresh/Brackish
Songor	Ghana	Restricted	Closed	74	0.1-2		Saline
Obidos	Portugal		1	6	2-3	4.5	

2.3 Coastal lagoons

The Oxford Dictionary of Earth Sciences approaches the definition of a coastal lagoon as a coastal body of shallow water (Allaby, 2008), characterized by a restricted connection with the sea, the water is retained behind a reef or island. Meanwhile, the Oxford English Dictionary allows two meanings of the word 'Lagoon' (Barnes, 1980) as area of salt or brackish water disjointed from the adjacent sea by a low lying barrier island; and a lake-like stretch of water enclosed in a coral atoll. Marrying the two definitions together, it is obvious that a lagoon is always a low lying coastal feature which is separated from the sea by a ridge or barrier and is connected to the ocean with a restricted channel. However, when the landed area of the coast is considered with its proximity to the sea, Mouillot *et al*. (2005) considered the lagoon in an interlink perspective as an interface area between the sea (salt or brackish water) and the land (where fresh water comes from). Hence, in a lagoon there are usually constant interactions of the sea and land activities at this border. These constant interactions bring about unambiguous relationship between the sea and the land and the seasonal changes to the salinity gradient of the coastal lagoon. A study carried out by Barnes (1980) gave a clearer hypothetical perspective of the salinity situation of the interface area (the lagoon) as a transition that could either be a hypersaline, sea-water dominated zone, brackish zone or freshwater dominated zone.

In further explanation of what the coastal lagoon is, Barnes (1980), estimated that "features less than 10m above sea level which are impounding, or have at one time impounded, bodies of water between themselves and the mainland" occupy 13% of the world's coastline and such water body could be term coastal lagoon (Knoppers, 1994). In terms of spatial spread, Mouillot *et al.* (2005) draws attention to the distinctive distribution of the lagoon as all over the world coastline, however, even though the lagoon occupies 13% of the world coastline, they are not equally widespread on the different coastal areas. In his excellent contribution Carter (1995) considered the spatial spread of global lagoons as 12% along the world's coastline.

In terms of basic features, Kjerfve (1994a) gave consideration to the coastal lagoons as identified by other authors to explain his definition of coastal lagoons. Lagoons are therefore identified and defined as inland water bodies found on all continents, usually positioned parallel to the coast and separated from the ocean by a sand barrier, connected to the ocean by one or more restricted mouths which remain open at least intermittently, and have its depth seldom exceeding a few metres. Unlike estuaries, coastal lagoons are describe by Adlam (2014) as systems that have restricted connections to the ocean and, in order to maintain that intermittent connection, also tend to have freshwater inputs relative to their size.

Furthermore, an interested definition of the coastal lagoon by Harris (2008) recognised the systems as estuarine basins where freshwater inflows are confined behind coastal dune systems, sand spits, or barrier islands which obstruct easy exchange with the ocean. This view is in support of costal lagoon definition by Kjerfve (1994a). The author identified lagoons as the most frequent systems in regions where freshwater inflows to the coast are small or mostly seasonal. The coastal lagoons with the other coastal ecosystems constitute a large part of the ecological richness of the biosphere (Contanza *et al.*, 1997). An idealized coastal lagoon has a barrier that separated it from the sea (Figure 2.2) and other coastal landforms.

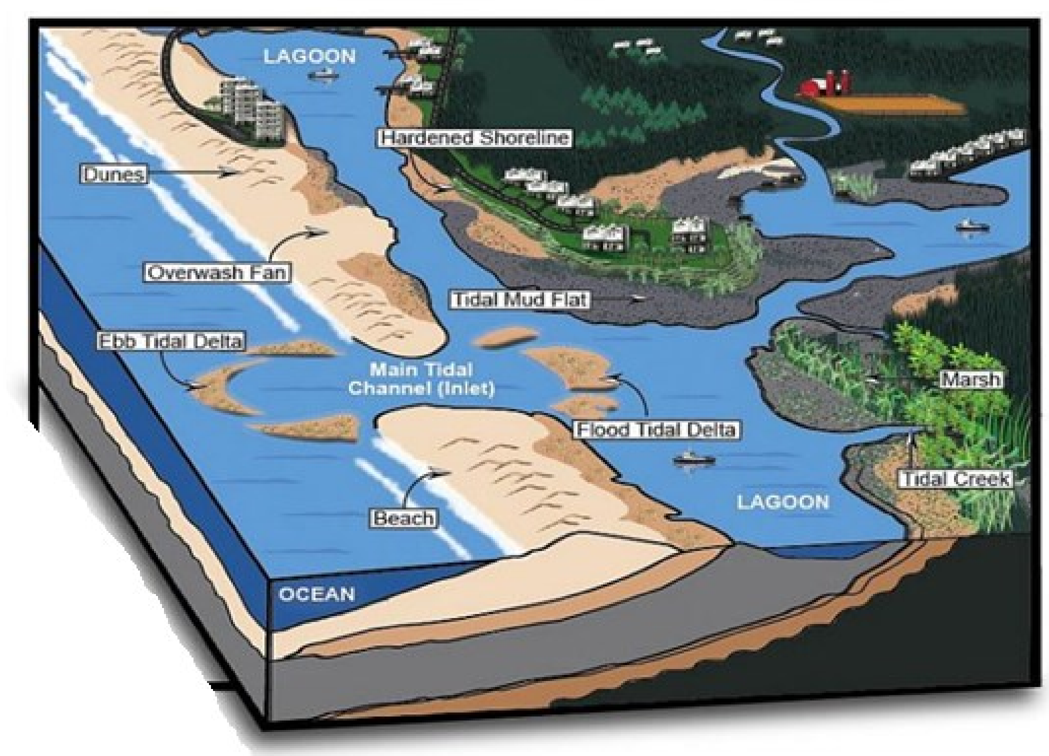


Figure 2.2: Idealized coastal lagoon showing important landforms and characteristics, adapted from (Anthony *et al*., 2009)

In summary, a coastal lagoon can be seen as a shallow water body that exists in the low-lying coastal plain, it always has a barrier island that separates it from the ocean and the system always has one or more connecting channel with the ocean, the connection which influences the hydrological behaviour of the lagoon depending on the dimension of the channel's cross-sectional area.

2.3.1 Origin and size of coastal lagoons

The genesis of coastal lagoons and the barrier island enclosing them depends primarily on the sea-level history of a region (Kennish & Paerl, 2010). In terms of climatic setting, there is no restriction to the formation of coastal lagoons. Coastal Lagoons exist where coastal embayment are separated from the adjacent sea by a barrier (Carter & Woodroffe, 1994). The barriers that separate the lagoons from the sea could at times be sand or gravel deposited by erosion and flood or is created by vegetation, coral growth or tectonics (Elliott & McLusky, 2002). Lagoons are best formed on transgress coasts going toward the landward area, especially where the continental margin has a low gradient and sea-level rise is low (Carter & Woodroffe, 1994). In terms of spatial distribution, they occur in tropical, temperate and cold coasts extending along 13% of the world coastline (Mouillot *et al.*, 2005). Even though coastal lagoons are found everywhere all over the world however, they are more common in low-lying coastal parts of the world where sea level, shore-face dynamics and tidal range are common parameters that influence their formation (Anthony *et al.*, 2009). Also, coastal lagoons can be recognised either in coasts where sea level has been rising (transgressive) or dropping (regressive). Formation of coastal lagoons was discussed by Anthony *et al.* (2009) as a system formed and nourished through sediment transport. The transported sediment is carried by rivers, waves, currents, winds and tides (Nichols & Boon, 1994) and gathers either in tidal deltas and rivers or on marshes and flats where immersed aquatic vegetation slows current movement.

Early research surrounding coastal lagoons focused on understanding processes of coastal lagoon formation, identification of defining characteristics, and the development of classification schemes within which to group water bodies that are similar in geomorphology. Coastal lagoon was described by Kjerfve (1994a) as:

"an inland body of water, usually oriented parallel to the coast, separated from the ocean by a barrier, always connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of metres".

Although some recent definitions (Bhattacharya & Giosan, 2003; Bird 2008) have considered deposition of sediment as well as littoral drift in an attempt to define coastal lagoon, the Kjerfve (1994a) definition is widely applicable in modern coastal science (Kjerfve, 1986). The identification and classification of coastal lagoons therefore becomes very complicated as a result of the overlap between definitions of lagoons and estuaries, the estuaries, though, are similar coastal systems but they are tidally dominated (Kjerfve, 1986).

Geological evolution of coastal lagoons is typically expressed in terms of the rate of basin fill through sedimentation, this is thus helpful to consider lagoon fill in terms of maturity (Roy *et al*., 2001). The geological evolution of coastal lagoons from unfilled to deltaic stage is described as a seamless progression (Roy *et al.*, 2001) that progresses correspondingly to the rate of sediment supply. In addition, Adlam (2014) used a model of geologic evolution to explain the formation of the coastal lagoons in geological scale. The model consists of two distinct phases (Figures 2.3a, b, and c) as: firstly the traditional view of supply-limited sedimentation and the secondly the constrained by additional factors that act to prevent sedimentation. The author found that the threshold between the two phases relates to depth and is defined as the depth at which wind waves are able to suspend sediments within the system central mud basin.

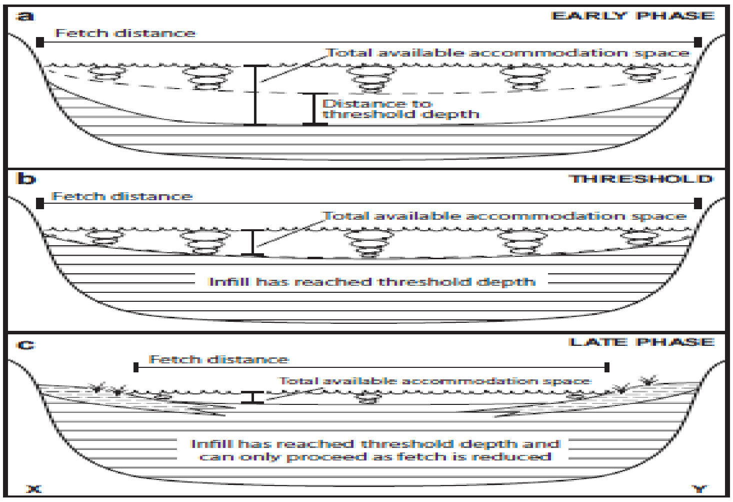


Figure 2.3: Schematic cross-sectional representation of two-phase geologic evolution of coastal lagoons, established by Adlam (2014)

If we consider geological time scales, coastal lagoons like estuaries are short-lived coastal features of recent origin. They are formed during the eustatic (uniform worldwide change in sea level) rise of sea level between the times of the Wisconsin glaciation 18,000 years Before Present (BP), and stand the risk of being completely in-filled by sediments or closed off from the sea by littoral drift (Kjerfve, 1986).

Various authors with different studies on coastal lagoons have consensus agreement on the depth of the lagoon all over the world, they all affirmed that lagoons are generally shallow with a few meters depth (Adlam, 2014; Anthony *et al.*, 2009; Barnes, 1989; Barnes, 1974; Barnes, 1980; Contanza *et al.*, 1997; Kjerfve, 1986; Kjerfve, 1994a; Kjerfve & Magill, 1989; Mouillot *et al.*, 2005). In terms of size, coastal lagoons can be features originating within a plain of beach ridges (good example is deltaic plain) or shallow basins existing in environments of over 10,000 square km (Fernandes, Dyer & Moller, 2005; Moller, Stech & Math, 1996) partially blocked by a barrier island (example is Lagoa dos Patos, Brazil).

However, being a shallow coastal feature, lagoons tend to be well-mixed (mainly by winds rather than by currents), and they vary from brackish to hyper-saline, depending on the geographic location which dictates the level of balance between evaporation, precipitation and river flow. In equatorial regions, lagoons can be hyper-saline during dry seasons as a result of low influx of fresh water and high intrusion of saline water. But the same lagoon may become entirely fresh during rainy seasons (Brown *et al*., 2006). Even though lagoons are shallow water bodies, the Lagos Lagoon which is the lagoon for consideration in my research has some parts around the inlets that are deep (12m – 17m) as a result of continuous dredging either for the purpose of sand mining and reclamation or for channel navigation.

In conclusion, the following factors size, prevailing seasonal condition, volume of human activities and the channel are among the factors which determine the particular morphology (form, shape or structure) and hydrodynamic characteristics exhibited by the coastal lagoon.

2.3.2 Morphology of coastal lagoons

Coastal wetlands and lagoons are generally separated from the sea by beaches, the genesis and evolution of the latter are essential for the overall dynamics of the entire coastal wetland or lagoon system. The specific morphology of each beach is the "mirror" of the way in which coastal sediments react to the local wind and wave regime (Stanica & Ungureanu, 2010). Changes in the structure of a lagoon could result from both natural (the predominant sedimentary processes - erosion, stability or accumulation) and artificial factors (influence of human activities). Knowing the sedimentology and geomorphology of the beaches and the wetland bordering coastal lagoons, some of the possible interactions between the marine coastal waters and the lagoon or wetland waters can be understood (Stanica & Ungureanu, 2010). Alves *et al.* (2009) use benefits transfer approach ("a method of taking the results or estimated benefits from previous valuation studies in different locations, modifying and transferring same to a policy or project to be evaluated" – (Desvouges *et al*., 1992, Iovanna & Griffiths, 2006)) to study morphological changes in the central Portuguese coast where the authors evaluated the ecosystem service losses from coastal erosion. In their study, it was discovered that urban rapid development influences changes in lagoon morphology especially those lagoons that have proximity to large urban settlements where population increases rapidly. The adoption of benefits transfer approach reveals that a very high rate of coastal lagoon ecosystem is lost to coastal erosion as a result of increased urban development (Alves *et al.*, 2009).

A morphological changes investigation by Pari *et al*. (2008) on the assessment of impact of 2004 Tsunami at the Vellar estuary, India, showed that coastal subsystems (lagoon) are formed by interaction of various processes and when the system suddenly undergoes impact of a natural hazard like a tsunami or storm surge, this brings the system under sudden extensive morphological change. A morphology change on the lagoon was assessed by the use of Real Time Kinematics GPS and GIS for mapping the coastal features. The result of the investigation shows that scientific understanding of the processes that controls any coastal lagoon is a main factor on which the strategies for management of the coastal lagoon depend. Such can be achieved by analysing morphological changes on various temporal scales (pre-impact, immediately after such impact and post impact analysis).

Another approach that has been applied more recently to study the morphology of a lagoon by many authors is to employ long-term morphological modelling to the tidal inlet of the lagoon (Cayocca, 2001; Michel & Howa, 1997; Ranasinghe *et al*., 1999; Roelvink, 2006; Roelvink, *et al.*, 1994). Although this approach cannot identify the changes that take place along the lagoon coastline or in its watershed, potentially it establishes both cross-shore and longshore sediment exchange. Roelvink *et al.* (1994) also discussed in his approach a number of different strategies of morphological updating as an important component of integrated modelling; among such strategies are the tide averaging approach and continuity correction method. Many of these studies acknowledge the limitation in their models as it is only applicable to a fractional part of the system which shows that the models are useful in depicting the morphological changes of a sectional area in the lagoon, but cannot depict broad implication of what goes on in the entire lagoon, especially, a lagoon of large surface area. Such models may not be applicable to the Lagos Lagoon situation with large surface area (460 km^2).

2.3.3 Lagoon's dynamics

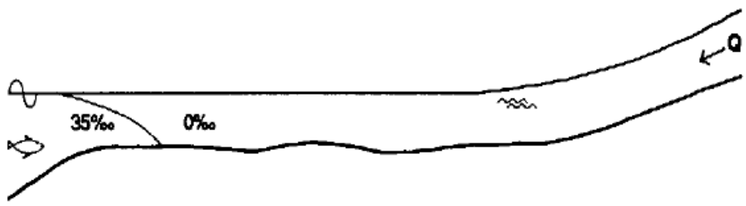
Most researches in these narrow shore-parallel coastal water bodies focused on the enclosed barriers rather than the lagoons systems (Hart, 2007). Most of the current models used in the study of changes in lagoon behaviour primarily explain such behaviour as being attributed only to freshwater inflow from the inlet river and also the intrusion of the sea water (Kirk, 1991). Even though the presence of the rivers that feed into the lagoons are identified as extremely important in carving out space for the lagoons, and for defining their physical scale, however, the assumption that lagoon behaviour can be predicted from river flow alone negates some evidence, including lagoon existence only on wave-dominated coasts (Forbes *et al*., 1995; Kirk, 1991; Orford, *et al*., 2002). Wave processes play important roles in changing a lagoon dynamics, especially at the highest river flow where they feed into the lagoon (Kirk, 1991). The dynamics of the lagoon could vary from coast to coast depending on the number of factors such as tidal incursion of the inlets, wave action, and river flow that impact the lagoons at their geographic location. Interestingly, as Hart (2007) rightly pointed out that most studies on lagoons are focused on the inlet changes and the enclosed barrier, not many publications are found regarding the effect of human activities on the main lagoon itself. Holistic studies on the coastal lagoons are needed in order to ensure an efficient management sustainability plan for the entire system.

Over the past five decades, many lagoons, estuarine and coastal waters have developed into the most fertilised environments in the world (Junior *et al*., 2013). The status of the coastal lagoon ecosystem is extremely vulnerable to the effect of eutrophic influence due to increasing human pressure; hence habitat modification and pollution become prevalent (Dumas *et al*., 2007). Eutrophication (which refers to the associated enhancement of primary production) has become a widespread water quality issue through numerous anthropic activities in lagoon ecosystems (Roselli *et al*., 2009). Eutrophication dynamics in any lagoon system are usually caused by multiple factors amongst which are: industrial activities, agriculture with associated fertilizer usage, rapid urban growth, untreated industrial discharges, and increase in burning of hydrocarbon fuels (Boesch, 2002).

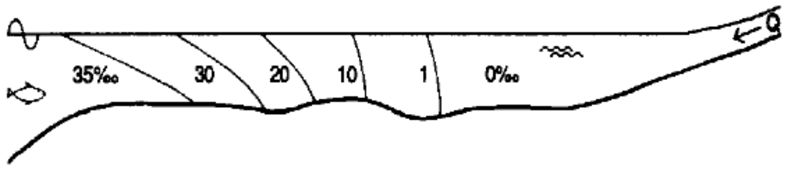
It could be rightly assumed that the increased wide spread growth of water hyacinths in Lagos Lagoon is a result of the increase in the yield of primary nutrients that support its dense growth. The impacts of eutrophication in the marine environment vary according to the enrichment level (Karydis *et al*., 2009). Various methods have been adopted for the quantitative assessment of lagoon eutrophication: statistical techniques, simulation models and water quality indicators being amongst the most widely used techniques. All of these methods aim at evaluating the environmental impact due to high concentrations of effluent discharge (Karydis *et al.*, 2009).

2.3.4 Type of salt intrusion in the lagoons

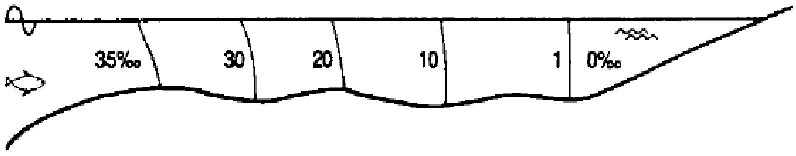
Sustainable water quality measures for the coastal lagoon could partly be achieved if there is good understanding about the system salt intrusion mechanism. The salt intrusion mechanism is generally divided into three (Savenije, 1992) as follows the stratified type or saline wedge type, the partially mixed type and the well mixed type. Figures 2.4 a, b, c illustrate the three types. A stratified condition occurs in a lagoon or estuary when the freshwater discharge into the system is large compared to the tidal flows. In comparison, a well-mixed condition exists in the lagoon when the freshwater discharge is small compared to the tidal flows. During the dry season, especially in the tropic region (latitude ±15° north and south), when freshwater availability is very low, demand for water is always at the peak. When the problems of maintaining an acceptable water quality are most pronounced (Savenije, 1992), salt intrusion is generally of the partially-mixed type.



a) Stratified condition



b) Partially mixed condition



c) Well-mixed condition

Figure 2.4: Three types of salt intrusion in the lagoon (adapted from Savenije, 1992)

The difference between a partially-mixed and well-mixed salt intrusion is unpredictable. The salt intrusion is generally referred to as well mixed when the stratification (different between the salinity at the water surface and the salinity at near the lagoon bottom divided by their average) is less than 10%. In practice, however, the value of 10% is not so important. Until the stratification threshold of 20% to 30% is reached, no serious drawback in applying well-mixed theory (Van Os, 1992). Generally in well-mixed lagoons the salinity reduces in upstream direction. Such a lagoon is referred to as a "normal" or positive lagoon. In a positive lagoon or estuary, the entire freshwater and the direct rainfall on the system surface exceeds the evaporation that takes place in the system (Dyer, 1973). This corroborated the claim made by Barnes (1980), that when classifying coastal lagoons the nature of its horizontal salinity gradients is controlled by the volume of freshwater, rainfall and salt water input. In some arid regions where there is a severe lack of water, negative or hypersaline lagoons or estuaries tend to exist, as the evaporation goes beyond the sum of the rainfall and runoff. Figure 2.5 illustrates the difference that exists between hypersaline and normal lagoon during salt intrusion process. In a hypersaline system, the salinity increases in upstream direction until it reaches a maximum after which it decreases based on the amount of freshwater inflow. Such hypersaline lagoons or estuaries occur in the Sahel (south of the Sahara Desert and north of the Sudanian Savanna) and in some tropical areas of North Australia (Pages & Citeau, 1990; Wolanski, 1986)

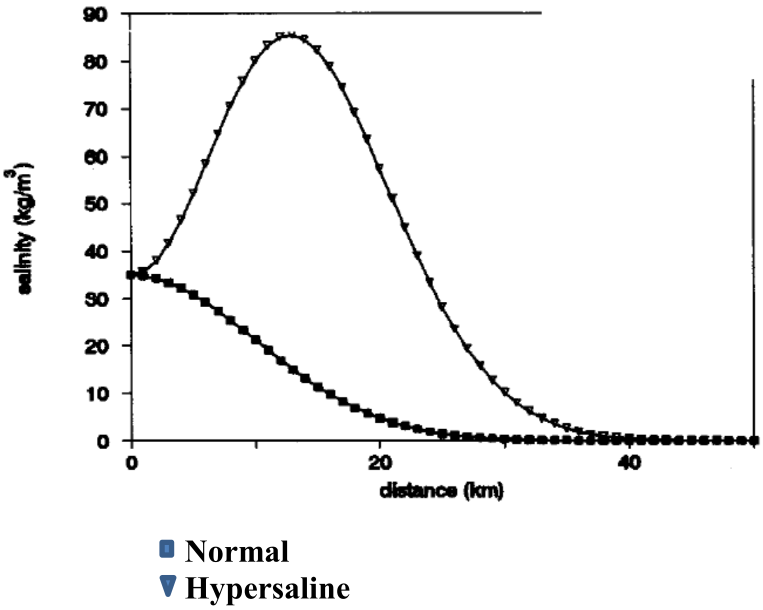


Figure 2.5: Normal and hypersaline lagoon/estuaries, adapted from (Savenije, 1992)

2.4 Lagoon's common global features

Most studies that have focused on coastal lagoons (Barnes, 1989; Barnes, 1974; Barnes, 1980; Carter, 1995; Carter & Woodroffe, 1994; Kjerfve, 1986; Kjerfve, 1994a; Kjerfve & Magill, 1989), have identified coastal lagoons all over the world as systems that are completely separated from the sea because of the requirement of their water to be marine, or at least brackish. Also characteristically, they have channels or a series of channels by which water is exchanged into the seas, more importantly, they are extremely shallow basins and are wave-dominated coastal systems. An overview of the basic characteristics features that are common to lagoons all over the world is provided in the next Section (2.4.1).

2.4.1 Lagoon entrance

Many studies on coastal lagoons from around the world (Adlam, 2014; Barnes, 1980; Bird, 2008; Carter, 1995; Harris, 2008; Kjerfve, 1986; Kjerfve, 1994a; Kjerfve & Magill, 1989) tend to agree unanimously that coastal lagoons usually have either one or more connections with the sea, and such connections are always narrow or moderately wide, the feature which causes intermittent interaction of the ocean water with the lagoon. The hydrological behaviour of the lagoons are generally influenced partly by its geography, partly by the size of connections from the sea and partly by the balance between the atmospheric precipitation, freshwater inflow rivers and rain on one hand and the amount of salt-water inflow from the sea on the other hand (Bird, 2008). Hence the type of lagoon that occurs on any particular coastal region is a function of the size of its entrance(s), the amount of freshwater and salt-water intrusion. These determine whether a lagoon is hypersaline, saline, brackish or freshwater lagoon (Barnes, 1980).

2.4.2 Low tidal range

Lagoon tidal range differs from region to region based on the configuration of the lagoon and the characteristics of its adjacent sea. However, studies of the world-wide lagoons show that they are confine to coastal plains with tidal ranges less than 4m (Davis & Hayes, 1984). Their energy regimes are dominated by internally generated wind waves (Bird, 1994; Bird, 2008; Harris, 2008). The low energy regime and reduced influence from ocean waves, tides and fluvial discharge provide opportunity for investigating a reduced number of processes (Adlam, 2014) in an otherwise complex environment, hence coastal lagoons are attractive natural workshops for studying processes that operate in coastal water bodies.

2.4.3 Characteristics nature of its water

The characteristic nature of lagoon water is a function of the geographical location and the prevailing climatic condition in the region where the lagoon exists. Based on where the lagoon exists, the nature of its water could either be freshwater, brackish, saline or hypersaline (Figure 2.6). Some lagoons are predominantly freshwater or brackish, while others are predominantly hypersaline. The dominant organisms in coastal lagoons reflect the balance of freshwater and marine influences; all lagoons are influenced by the local biogeography. Thus, the dominant species in Northern Hemisphere lagoons are quite different from those in their Southern Hemisphere equivalents. Different coastal regions of the globe differ in their biodiversity; for example, the endemic biodiversity of seagrasses is very high in Australian waters (Harris, 2008).

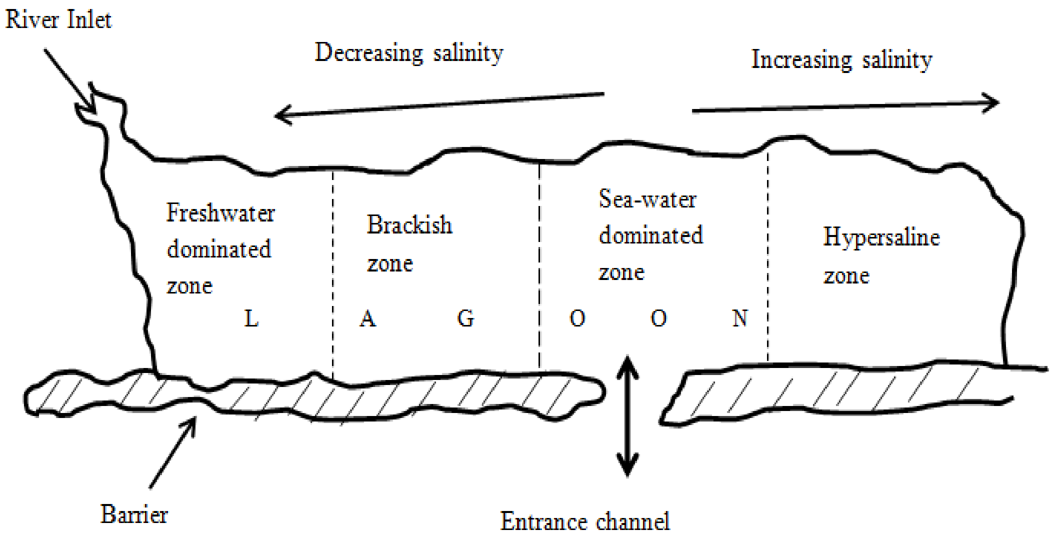


Figure 2.6: A hypothetical lagoon showing the four types of environment which may occur (Many lagoons may comprise only one or two of these environments) - (Barnes, 1980)

2.4.4 Rich productive zone

Coastal lagoons are usually among those marine habitats with the highest biological productivity (Alongi, 1998), functioning as nurseries and feeding platforms for opportunistic coastal landform habitats and sustaining important fisheries (Clark, 2009). Kennish and Paerl (2010) ranked the coastal lagoons as among the most productive ecosystems on earth and found that they provide a wide range of ecosystem services and resources. More simply, but still emphasising the rich productive nature of coastal lagoons, with the other coastal ecosystems, the lagoons constitute a large part of the ecological or conservative richness of the biosphere (Costanza *et al*., 1997). Many coastal lagoons, notably those with restricted circulation, high rate of freshwater inflow, low flushing rates as a result of narrow connection to the sea, and relatively long residence times, are especially susceptible to nutrient enrichment from surface run-off, groundwater and atmospheric inputs (Kennish & Paerl, 2010).

For further instances of this, due to the interaction between the lagoon interface area with freshwater inputs from the watershed and marine influence from the sea via the connecting channel, and their shallow depths, Knoppers (1994) noted that lagoons are very productive ecosystems (on average yielding 300 g C m^{-2} y^{-1}), but they are also very sensitive to both climatic and human activities. As a result, these environments are of great social concern and constitute one of the main priorities in the integrated management of coastal areas due to their vulnerability to human impacts and the intensification of competing uses (Pérez-Ruzafa, *et al*., 2007). Since coastal lagoons are often very productive this makes them ideal for aquaculture programmes; notwithstanding they are at the same time highly stressed by human activities (Kjerfve, 1994b).

2.4.5 Shallow depth

Coastal lagoons exist at low lying areas of the coast, hence they are characterised by shallow depth. In terms of geological age and regions where coastal lagoons are formed globally, they are generally about 6,000 years old, having formed where valley mouths or low-lands have been submerged by the sea during the later stage of the worldwide Holocene marine transgression (Bird, 2008).

In conclusion, coastal lagoons have been originated by marine submergence, and then partly or totally enclosed by longshore barriers. They have one or more connections generally sustained by tidal ebb and flood, and intrusions of sea water through the connections give way to hypothetical salinity gradient from saline through brackish to freshwater at river inlets. Tidal range in a lagoon usually diminishes from the salt water entrance toward the upland region, but in hypersaline lagoons the concentration of the salinity does not reduce to a very low value. Waves and currents may reshape lagoon shores, eroding bays and building barriers, leading eventually to segmentation into smaller lagoons (Bird, 2008). Lagoons are greatly influenced by ecology, particularly where response to salinity changes is very strong, hence, freshwater marshes encroach the lagoon if they become fresher with high inflow of freshwater, but if salinity increases there is likely to be erosion of areas formerly with freshwater swamps due to die back of the vegetation.

2.5 Classification of coastal lagoons

Shallow coastal shelf systems are widespread all over the continental boundaries. Mixing of upland or offshore waters takes place in these regions. Mixing zones are basically characterised by the presence of substantial salinity gradients, they are located either in inshore basins or partly offshore (Dronkers, 1988). Different types of coastal systems can be distinguished and several classifications have been proposed, for example by Hansen and Rattray (1966) and Schubel (1971). These classifications can be based on either hydrodynamic or geomorphological properties, or on a relationship combining both aspects.

The dynamic nature of the coastal lagoons and the close similarity that occur among coastal landforms makes it a bit difficult to differentiate and as well classified coastal features. Notwithstanding, a significant body of literature exist on the investigation of coastal systems and their landforms (Barnes, 1980; Biggs & Cronin, 1981; Dyer, 1973; Flemer et al., 1983; Jay, Geyer & Montgomery, 2000; Nichols & Allen, 1981; Umgiesser & Zonta, 2010) and have been able to draw line of distinction to differentiate various coastal features. As a consequence of this, some of the works conducted on coastal systems (Brehmer *et al.*, 2011; Johnston & Gilliland, 2000; Nairn *et al.*, 1998; Seixas, 2002) have been able to showcase investigations on coastal lagoons and their classification (several classification schemes developed for coastal lagoons are discussed in Sections 2.3.1 to 2.3.3). Four lagoon types were identified by Nichols & Allen (1981): estuarine lagoon, open lagoon, partly closed lagoon, and closed lagoon. These are based on dominant processes. Whereas, Kjerfve (1986) classified lagoon systems into 'choked', 'restricted' and 'leaky', based on the nature of the outlet and water exchange between the lagoon and ocean. In addition to these broadly applicable categories, researchers have often subdivided these or created their own classification scheme to distinguish unique water body types in their area of interest. Lagoons can conveniently be classified using some basic classification parameters (Umgiesser & Zonta, 2010), such as salinity distribution, flow rate and circulation, water exchange and classification based on residence time. Based on these parameters, the classification of coastal lagoon is discussed thus.

2.5.1 Classification based on salinity distribution in the lagoons

This classification tends to distinguish the lagoon water profile through the vertical salinity distribution. Umgiesser and Zonta (2010) suggested that in applying this classification technique, it is reasonable to consider lagoon definition in two perspectives. First is the definition that embraces the fact that: "a lagoon is a semi-enclosed coastal body of water with open access to the sea, the channel with which sea water entering into the lagoon is measurably diluted with fresh water from upland". Lagoons described by such a definition are referred to as *positive* lagoons. Alternatively, the second definition is based on the assumption that intermittent closure of the lagoon to the sea may occur and equally rate of evaporation exceeds input of freshwater from rainfall and rivers into the lagoon system; any lagoon that falls under this condition is classified as a negative lagoon. Using these definitions, Umgiesser and Zonta (2010) in corroborating the works of Barnes (1980) and Savenije (1992) suggested a possible classification of lagoons with the aid of its vertical salinity distribution (Figure 2.5).

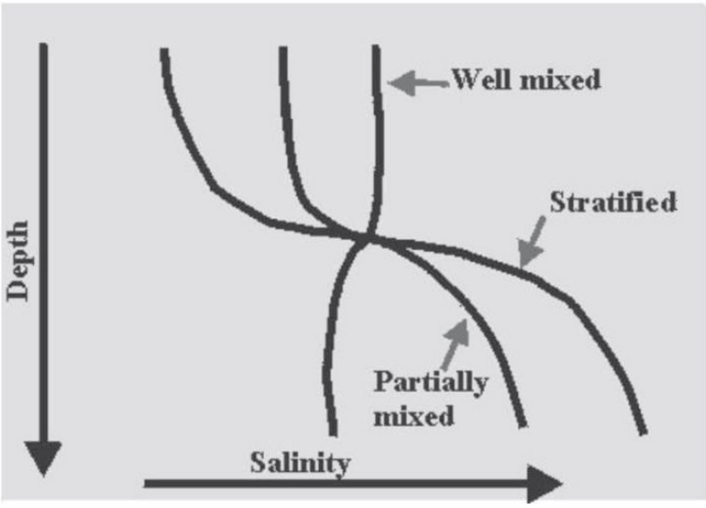


Figure 2.7: Different type of lagoon mixing with variation in vertical salinity (adapted from Umgiesser and Zonta (2010)

Lagoon circulation according to the above diagram and the initial definitions from Umgiesser and Zonta can generally be classified into highly stratified lagoons (when the freshwater discharge into the system is large as compared to the tidal flows), slightly stratified lagoons or partially mixed lagoons (threshold between stratified and partially mixed), vertically mixed lagoons (the freshwater discharge is small as compared to the tidal flows) and hypersaline lagoons (this is very common in the arid region where water is scarce).

2.5.2 Classification based on flow rate and circulation

In early classification of the Chesapeake Bay by Flemer *et al.* (1983) consideration for estuarine circulation was very dominant. A very useful and significant index for this type of classification is the flow ratio which is the ratio of the volume of freshwater entering the lagoon during a tidal cycle to its tidal prism. Interestingly, Biggs and Cronis (1981) use the flow ratio index to classify estuaries and the classification is also very applicable to coastal lagoons. The classification is in three parts, if this ratio is approximately 1.0 or greater, the estuary (lagoon) is normally highly stratified; for values near 0.25 the system is normally partially-mixed and for ratios considerably less than 0.1, it is normally well mixed.

If we consider the ratio of freshwater to tidal prism on semi-enclosed coastal water body, other possible classification methods focusing on tidal amplitude to mean depth and other parameters, have been evaluated by Jay *et al*. (2000). They emphasis the predictive ability of these simple parameters with regards to salt transport needed to maintain salt balance. Authors such as Dyer (1973); Fischer (1976); and Oey (1984) employ two basic classification parameters: (i) stratification $\Delta S/S$, a ratio of top-to-bottom salinity difference to vertical average salinity; and (ii) circulation U_s/U_f, a ratio of surface velocity to vertically average net flow. Furthermore, with the consideration of water exchange processes in shallow coastal systems, Dronkers (1988) suggested an estuarine or lagoon classification using the system exchange processes like river flow, tides and waves as affecting mixing and fluxes of energy and material. This water exchange classification approach is broadly explained in section 2.3.3. In his classification, he distinguishes different types of shallow coastal systems. The classification suggests that the variation of river flow relative to hydrodynamic residence time can be important for the salinity properties and observed patterns inside the system.

Kjerfve (1994a) subdivided coastal lagoons into three geomorphic categories: choked, restricted, and leaky lagoons; these represent three points along a spectrum reflecting the exchange of water with the coastal sea. The rate and magnitude of oceanic exchange reflect both the dominant forcing functions and the time-scale of hydrological variability. Physical gradient with the lagoon environment can be supposed to have direct relationship with the biological gradients in species richness, abundant and productivity.

2.5.3 Classification based on water exchange

Another method of lagoon classification and the most interesting of them all is classification using the water exchange pattern of the lagoon with the adjacent sea. A dominant physical factor in lagoons is the tidal amplitude, which provides a means of classifying these systems relative to their sensitivity nutrient supply (Umgiesser *et al*., 2004; Umgiesser & Zonta, 2010). In comparative analysis of data from 40 micro-tidal and macro-tidal (Davies & Moses, 1964) lagoons/estuaries Monbet (1992) discovered that macro-tidal systems generally exhibit a tolerance to pollution despite high loading originating from freshwater input.

Three geomorphic types of lagoons according to their water exchange with the coastal sea can be found under this classification (Kjerfve, 1986), (i) choked lagoons, (ii) restricted lagoons, and (iii) leaky lagoons. Detailed descriptions of each of these are given below.

Choked lagoons

These types of lagoons occur along the coast with high-energy and significant littoral drift coastlines and have a series of compact cells, connected by one single and narrow outlet, the narrow outlet causes restriction in the lagoon water exchange with the sea (Kjerfve, 1994a; Umgiesser & Zonta, 2010). Although lagoons experience tides that co-oscillate with other tides in the coastal ocean, the entrance of a choked lagoon serves as a dynamic filter which largely eliminates tidal currents and water-level fluctuations inside the lagoon (Kjerfve, 1986). Choked lagoons have a peculiar characteristic noticed by Kjerfve (1986), as a system where tidal oscillations are often reduced to 5% or less as compared to the adjacent coastal tide. Good examples of choked lagoons include Lake Songkla in Thailand, Lagao dos Patos and Lagoa Araruama in Brazil, Lake St. Lucia in South Africa and the Coorong lagoon, Australia (Kjerfve, 1994a; Kjerfve, 1994b; Perillo, 1995).

Restricted lagoons

Restricted lagoons are however different from choked lagoons in that they consist of two or more entrance channels which make the system restricted compared to its large and wide water body oriented parallel to the shore (Phlips *et al*., 2002). Consequently, restricted lagoons have a well-defined tidal circulation (Kjerfve, 1986), hence, a well-defined exchange with the ocean and tend to show a net seaward transport of water. These lagoons exhibit mostly vertically well mixed condition and depict salinities from brackish water to sea salinities. Due to the restricted connecting channel with the sea, the systems can be incapacitated in their ability to flush external substances at a faster rate consequent upon this is poor water renewal and other water quality problems (Guyondet & Koutitonsky, 2008).

Leaky lagoons

They are usually elongated shore-parallel lagoons with many entrances with the sea, hence wide tidal channels which provide sufficient tidal currents that overpower the wave and littoral drift action that want to close up the lagoon channel entrance. This type of lagoon is characterised by various wide tidal passes, unharmed exchange of water with the ocean on strong tidal currents, tide, wave and salinities close to that of the ocean (Kjerfve, 1986). Examples of leaky lagoons are Mississippi Sound (Gulf Coast, USA) and Waddenzee (Netherlands).

2.6 Descriptive hydrodynamic and morphological changes in coastal lagoons

Composition of the lagoon inlets and outlets, types of vegetation around the lagoon, its spatial location, topography and influence of human activities around the lagoon determines the morphology of any lagoon ecosystem (Debenay *et al*., 1998). While combination of wind, tide, inlet and outlet dimension, river input, salinity intrusion, seasonal climatic variation, heat balance and induced human activities are the major factors that influence hydrodynamic nature of a lagoon (Debenay *et al.*, 1998). The concentration of human population around the coastal zone is an indication of increased human activities around the coast, including the lagoon environment. As a transition space between land and sea, coastal lagoons are characterized by a high rate of dynamic change in the natural environment, a high rate of human population growth and economic development, accompanied by a high rate of degradation of natural resources (Lloret *et al.,* 2008).

The range of investigations on lagoons, have little scientific work done on them when compared to investigations on estuaries. Kjerfve (1986) assumed that one of the reason for this might be that coastal lagoons are shallow, less suitable for harbours, and thus often without major population centres; however this is not true about Lagos Lagoon, the system has concentration of the most populous Nigeria city around it. Lagos Nigeria with population of approximately 17 million people and the biggest seaport in Nigeria is situated around the Lagoon. Rather than having fewer population attraction as claimed by Kjerfve, the location of the Lagoon attracts a huge population and so many industrial settlements are concentrated around the Lagoon system.

A simple view of the body of water of the coastal lagoons show that the system is influenced by the same forcing just as in coastal plain estuaries yet the experience differs slightly from that of the estuaries. Estuaries and coastal lagoons are driven by tides, river input, wind stress, and heat balance at the surface, but respond unequally to these forcing functions because of differences in geomorphology (Kjerfve & Magill, 1989). Whereas circulation, mixing and exchange have been studied extensively in coastal plain estuaries, these processes have been less well synthesized for coastal lagoons. Even though hydrodynamics in coastal lagoons are influenced by tidal forcing from the ocean, the response of a coastal lagoon to tidal forcing depends on factors such as morphology of the system, friction, depth variation, and changes in cross-sectional area at the inlets and throughout the system (Serrano, *et al*., 2013). Excluding the factors identified by Serrano *et al.*, (2013) a further study on Patos lagoon, Brazil done by Moller *et al*., (2007) reveal other factors by which coastal lagoons can further be distinguished. The authors noticed that coastal systems are influenced by the tidal signal coming from the ocean, apparently, the lagoon water produce a response that will basically depend on factors such as depth variation, morphology of the system and entrance channel, hydrological effects (Pugh, 1996) and river discharge. This tidal forcing effect can induce residual currents, over-tides, tidal asymmetry, and amplification or attenuation of oscillations inside a coastal lagoon (Möller *et al.*, 2007). Tides are distorted as they propagate into shallow water of coastal lagoons and estuaries and generate higher-frequency over-tides. Non-linear terms associated with friction, advection and conservation of mass are responsible for the production of the fourth-diurnal (M4) lunar harmonic in lagoons and estuaries (Friedrichs & Aubrey, 1988).

2.6.1 Nature of the coastal lagoon inlets

Previous studies that have been reviewed so far in this research shows that the configuration of the lagoon river inlets are lacking in quantitative data when it comes to data on daily or seasonal variations in wave intensity and direction. In almost every case, the channels that connect the lagoon to the ocean are of paramount importance to the economic development of the coastal country where such lagoon exists. For this reason, constant maintenance dredging is done for the improvement of such channels and always fixed stabilization structures are put in place as a prerequisite to the growth of ocean transport (O'Brien, 1976). For instance the inlet that connects Lagos Lagoon to the Atlantic Ocean receives more attention than the river inlets which bring freshwater into the Lagoon. A whole organisation (Lagos Channel) is committed to the constant maintenance of the channel to ensure safe navigation.

The lagoons water balance has two distinct regimes. The first is the tidally dominated condition; in this case the lagoon entrance is opened (Figure 2.8). The second regime is governed by the balance of inflows and outflows which occurs when the entrance of the lagoon is closed.

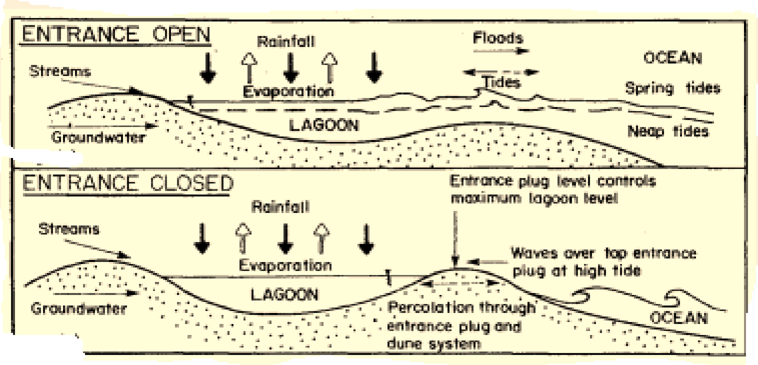


Figure 2.8: Lagoon water balance, adapted from (Gordon, 1990)

With the entrance of the lagoon open, the water level in the system is determined by the tidal forcing at the lagoon entrance where it boarders the ocean and by the flood event that is produced by the freshwater inflows and occasional rainfall input. The tidal phase lag and head loss through the lagoon entrance combine to elevate or increase the mean daily water surface of the lagoon (Figure 2.9).

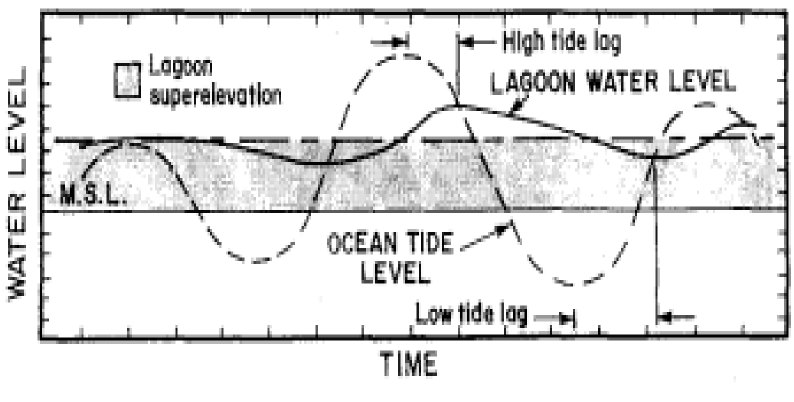


Figure 2.9: Lagoon tidal elevation, adapted from (Gordon, 1990)

On the other hand, when the entrance of the lagoon is closed, the mean lagoon water level is dictated by the inflows – that is: the river, groundwater, and direct rainfall on the lagoon’s water surface; and also the outflows – that is: evaporation and percolation through the sand barrier (Figure 2.8).

Several environmental factors influence the configuration and existence of the coastal lagoon inlets, the factors are discussed under paragraph *a* - *c* below:

Freshwater inflow: Freshwater discharges in the lagoons are minor compared with estuaries (O'Brien, 1976). The rate and volume of freshwater inflow to the lagoon affects the balance between the ebb and flood phases of the tides, current flows, and the ability of the inlet to reopen after closing. However, the discharge rate of freshwater determines the tidal prism and the process of mixing with the freshwater inflow.

Tides: Tidal prism in any inlet is a major factor in determining the flow of the cross section of the inlet. The absolute size characteristic of a lagoon inlet can be determined using the tide range to the depth of the inlet and the dependent variation in flow cross section between high water and low water. Since average depth in coastal lagoons is very shallow, the tidal range and tidal prism will be affected by the nature of depth because the tide wave traverses the lagoon at a speed that depends on the depth. Board (1987) remarks that increase in mean sea level will result in increased volume of water leaving the lagoon at ebb tide (tidal prism). Such an increase in tidal prism is as a result of inundation and shoreline retreat and by a reduction of friction in tidal entrances. Study by O'Brien (1976) shows that there is an equilibrium relationship between the tidal prism of a lagoon and the cross-sectional area of the entrance. Hence, increased tidal prism will cause an increase in the tidal entrance area. In their work Carniello *et al.* (2005) used a numerical model that combines wind wave and tidal fluxes in a tidal basin to do a numerical simulations reproducing the wind wave field inside the Venice lagoon under different wind and tidal conditions and the various model results obtained were compared with recent field data collection in different stations in the lagoon. The work equally evaluated bottom shear stress distributions in order to assess the potential for sediment resuspension in shallow tidal basin due to combined action of tidal currents and wind waves. The work revealed evidence of the complementary effect of tidal currents and wind waves on bottom shear stresses that is present inside the lagoon.

Longshore transport and wave climate: The sand transport and deposition alongshore towards the inlet influence the configuration of the lagoon inlets. In a coast where we have strong influence of longshore current that transports sand, the inlet from the ocean to the lagoon is a repository for sand deposition since the longshore wave is more powerful than any local wave from the lagoon. As a result of this, many lagoon inlets are protected with engineering structure that prevents accretion of the longshore sand transport. A good example is the breakwater (East-mole, Figure 2.10) built across the pathway of the longshore current around Lagos Lagoon inlet to the Atlantic Ocean.

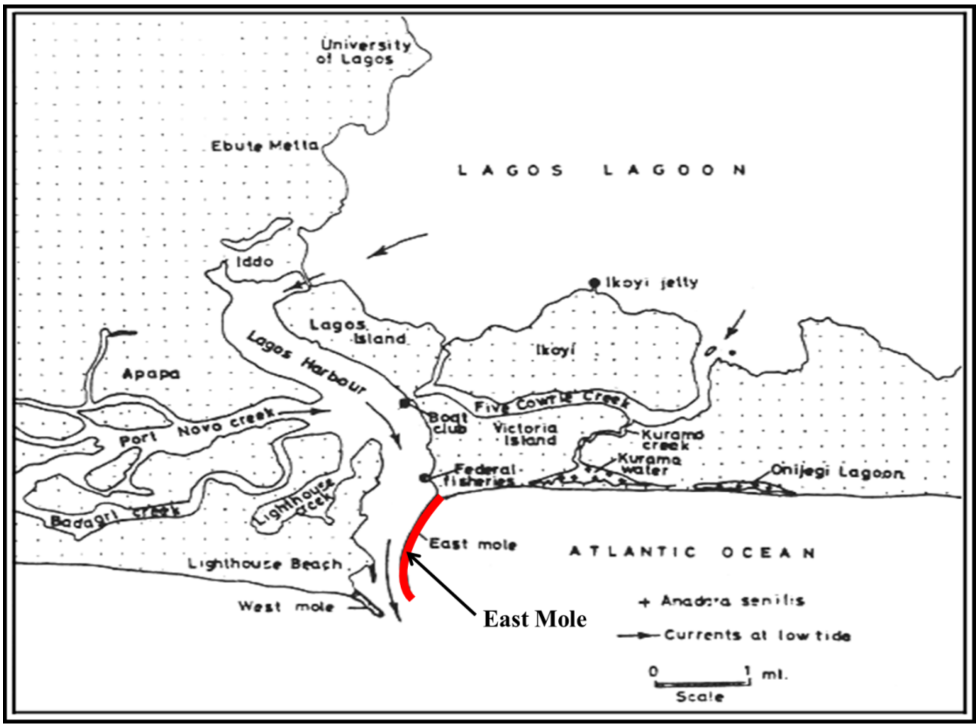


Figure 2.10: Map showing Lagos Lagoon and its entrance into the Atlantic Ocean, the entrance is bounded by the east mole at the eastern region of the to prevent accretion of sand carried by longshore current (Adapted from Afinowi, 1975)

2.6.2 Atmospheric conditions

Coastal lagoons and other shallow coastal water bodies are ecologically important ecosystems (Dyer, 1973). In spite of ecological relevance of lagoons and other shallow brackish systems, relatively few studies have been devoted to investigate on the factors that control system atmospheric conditions and Ultraviolet Radiations (UVR) attenuation in these ecosystems (Gouveia et *al*., 2015; Piazena & Häder, 1994). All shallow brackish systems are characterized by the intense exchange of waters with different concentrations of dissolved organic matters that absorb UVR (Stedmon *et al*., 2000). Some of the early studies reveal that an exchange that happens between the freshwater and salt water with high and low Dissolved Organic Matter (DOM) concentrations are the major process that governs underwater UVR attenuation in in shallow water brackish systems (Conde *et al*., 2000).

Studies about the atmospheric condition of the lagoons is not very common, hence literatures on this area is very scarce. The fact that coastal lagoons are very shallow and effective mixing is a gre*a*t possibility; prevailing atmospheric gas around the lagoon can be uniformly distributed along the vertical profile of the lagoon water (Piazena & Häder, 1994). This could endanger the lives of the habitat living within the ecosystem, especially where a lot of toxic industrial gas is released into the atmosphere surrounding the lagoon.

The climatic condition of an environment indicates a lot about the prevailing temperature, humidity, evaporation and precipitation of such geographic locations. In a recent study of the mesotidal Ria Formosa, a coastal lagoon in Portugal, it was observed by Newton & Mudge (2003) that temperature in the lagoon channels ranged from 12°C in winter to 27°C in summer and the corresponding salinity from 13 to 36.5. Where there is a large difference in climate condition around a lagoon, despite the fact that the system is very shallow, heterogeneous conditions could result in the stratification and mixing of the system. The meteorological effects (wind and air temperature) induced on a lagoon systems are essentially seasonal depending on its geographic location, hence, the meteorological condition influencing the surface water temperature of the system (Vaz *et al*., 2009).

Theoretically, when wind starts to blow over smooth water there are small frictional effects, these create cat's paws and then ripples on the water. As the wind increases, the ripples get larger until they soon become large enough to be pushed along by the wind. However, the movement of these wavelets is slower than the wind and the pushing of the wind on them causes an increase in size until they become steep enough to break. This suggest that around a lagoon where the wind speed is always very slow in a direction against the water current, turbulence effect on such system will be minimal. In contrast, if the wind speed surrounding a lagoon area is very high against its water current, there is bound to be turbulence over the system water (Hristov *et al*., 2003).

However, wind waves are a local manifestation of the energy that has been transferred to the sea from the wind; this energy travels down-wind away from the source area, rather like ripples in a pond when a stone is dropped in, or from the bow wave from a ship. These waves that move away from their source are known as swell (Donelan *et al*., 1997). The stronger the winds at the source area, the bigger will be the swell and the further will it travel. The longer that the wind blows in the source area, the longer will the swell persist, even long after the wind has ceased or changed direction. When winds blow across water, the frictional drag causes water to be pushed across the area over which the wind is blowing. To the contrary, when the wind stops blowing, the water tries to return to its normal level but the momentum of the moving water can cause an overshooting effect and the water piles up on what was the windward side.

In coastal lagoons, the wind, acting on time scales ranging from a few days to a seasonal basis (Pitts, 1989), is considered to exercise a major influence on their dynamics due to the fact that the tides are generally of secondary importance and are quickly damped out by frictional effects at the entrance (Kjerfve & Knoppers, 1991). The wind drives circulation through its local and non-local effects. The former is associated with wind that stresses the lagoon waters to form the set up/set down oscillations while the latter is related to coastal water level variations caused by Ekman transport mechanism. The relative importance of the local and far field wind on lagoon and estuarine circulation has been extensively discussed since the paper of Weisberg (1976). The frequency dependence of their effects has been reported by Smith (1978) and Su & Chen (1992) who have also concluded that the remote forcing was always the dominant one. According to Garvine (1985) the estuarine circulation is normally driven by the far field wind because of the relative shortness of most of the estuaries with respect to the low subtidal wavelength.

2.6.3 Lagoon water tide and hydrodynamic modelling

The ocean tide generated by the gravitational attraction of the moon and the sun, can be represented by the sum of a finite number of sinusoidal or harmonic constituents, grouped into three basic types: (i) semi-diurnal, with a period of about half day; (ii) diurnal tide, with a period of about one day; and (iii) the long-period tide which includes all tidal oscillations with period ranging between 14 days and 19 years. With relatively small dimensions and depth of most shallow water bodies compared to the massive ocean, the direct effect of the gravitational attraction of the moon and the sun on their waters (that is, the shallow systems) is very negligible. Hence, the tide within the lagoon and other shallow systems is majorly influenced by the co-oscillation force by the ocean tide at their entering channel.

While the tidal wave propagates into shallower waters within the estuary or lagoon, it becomes distorted due to several physical processes, including reflection at the head of the estuary or lagoon, which is responsible for standing-wave generation and local resonances (Pugh, 1996). Figure 2.11 shows the relationship between water level and tidal current, unlike Figure 2.10 that depicts tidal phase lag and head loss combine to elevate the mean daily water surface of a lagoon. Figure 2.11 shows the case of tidal current with standing and progressive contributions, in a standing wave system, the tidal elevation and the associated current velocity are 90° out of phase, implies that reverse of a tidal current from ebb to flood or vice versa will be simultaneous either with high or low water (Figure 2.11 (b)). If the energy of the tidal wave is completely dissipated by friction before reflection takes place, then the tidal wave becomes purely progressive (Figure 2.11 (c)). In this case, tidal elevation and currents are in phase, meaning that maximum flood (ebb) currents occur at high (low) water. In most shallow-water landforms, including lagoons, the tidal waves are a mixture of standing and progressive contributions (as in Fig. 2.10 (d)) and the progressive wave contribution can be estimated by the time difference between high or low water and the respective slack water (Dyer, 1997).

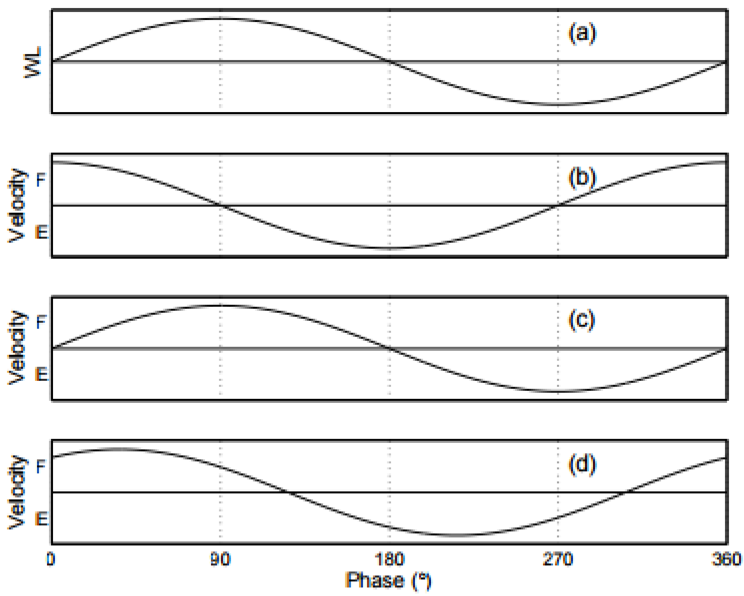


Figure 2.11: Symbolic water level (WL) (a) and corresponding velocity variation during one tidal cycle for (b) a pure standing wave, (c) a pure progressive wave and (d) a combination of the two – E = Ebb tide; F = Flood tide

In lagoons and estuaries shallow waters, the tidal range frequently becomes a non-negligible fraction of the total water depth and has to be considered for the tidal wave rapidity as expressed in equation 2.1

$r = \sqrt{g(H + \zeta)}$ 2.1

Where g is the acceleration due to gravity, H is the water column mean depth and ζ is the water surface elevation relative to the mean depth (Neves, 2010). This means that the wave crest moves faster than the trough, resulting in shorter and more intense flood than ebb currents. Bottom friction is also an important factor that affects tidal wave propagation in shallow waters, delaying the water movement. This is a non-linear process since it depends on the square of the current velocity. Therefore, propagation of the tide in shallow waters develops time asymmetries in the rise and fall of the water surface, as well as in the duration and magnitude of the tidal currents.

Tidal dynamics of shallow lagoons and estuaries is a complex matter because of the growing population around the coast; this has attracted the attention of a large number of researchers over the last few decades (Dias *et al*., 2013). Recently, Neves (2010) described the role of the main forcing mechanisms on the lagoon/estuarine and shallow water dynamics, in his finding, he discovered that tide is the systems' key forcing mechanism, and that river discharge influences the water column stratification in a seasonal time scale.

Many studies have used tidal model to investigate the tidal condition of lagoon system (Araújo *et al*., 2008; Carniello *et al.*, 2005; Dias *et al*., 2000; Marinov, Norro & Zaldívar, 2006; Montaño-Ley *et al*., 2007; Picado *et al*., 2010; Vaz *et al*., 2009). Araujo *et al.,* (2008) used both analytical and hydrodynamic models to examine the cause of tidal changes in the Ria de Aveiro lagoon, Portugal and found out that the system exhibit an average increase of 0.245m in M2 amplitude and an average of 17.4° in M2 phase between 1987 and 2004. This suggests that the lagoon has undergone stress that results in the increased amplitude of its tide. Even though numerical models provide detailed information of the tidal response to changes in the parameters representing the complexity of processes accountable for the changes, nonetheless numerical models are not always the quickest and simplest method of analysing the sensitivity of the tidal response in any lagoon. This suggests that there is need for application of two or more different methods the results of which can complement each other and be applied to single inlet systems and yet accomplish a reliable result. Previous mathematical model (Dias *et al*., 2000) applied to the study of tidal propagation on the system concluded that tidal range increases during spring tide at a far end of the system channels which agreed with a local increase of the tide level.

Furthermore, the tidal hydrodynamics of Topolobampo lagoon in Mexico was investigated by Montano-Ley *et al.* (2007) using a modified two dimensional non-linear hydrodynamic finite difference model. The model found some perfect agreement between the maximum predicted tidal currents (0.85 m/s) within the channel and the direct field measurement. The model has found its usefulness in predicting and determining the tidal prism through the system channels in different tidal conditions.

However, the hydrodynamics of coastal lagoon processes are very susceptible to external forcing conditions. Changes to these conditions as a result of natural and human induced (anthropic) activities can have huge effect on the system. Models that could be appropriate in studying hydrodynamics of any lagoon based on its shallowness include models based on finite element method, MIKE 21 and MIKE 3 Flow Model (Umgiesser *et al.*, 2004). It must be noted that one off seasonal data is not enough to validate the result of such a model, data that covers several years are needed. The MIKE 21 & MIKE 3 Flow Model FM simulate unsteady flow taking into account density variations, bathymetry and external forces. The choice between 2D and 3D models depends on a number of factors (river inflow, wind stress, water elevation, and tidal structure among others). For a shallow water body like a lagoon that this research is dealing with, wind and tidal currents are often sufficient to keep the column salinity and temperature homogenous. A 2D model is quite often chosen for researching into lagoons because of the assumption that there is no density variation in the vertical column because of the fact that lagoon tidal current and wind are enough to keep its water column well-mixed (Umgiesser *et al.*, 2004).

Several hydrodynamic models have been used to carry out different investigations on the coastal lagoons, such models include MOHID water modeling (Kenov *et al.,* 2012; Martins & Fernandes, 2004), TELEMAC – 2D and 3D (Martins & Fernandes, 2004), DELFT3D-ECO, DELFT3D- SED (Blauw *et al.,* 2009). One important observation with the use of all these models is that despite the good results achieved with the use of models to make different investigation in the coastal lagoons, none of the models could a give good result without embarking on collecting a series of relevant experimental data. Such empirical/experimental data help in simulating, validating and testing such a model. In a situation where there are no available data, it is always good to embark on evidence based (experimental) method in achieving the desired results. Hence it could be concluded that no model is good without a series of evidence based data for the model validation. This is one reason that strongly backs up the need for experimental/field observation research in the Lagos Lagoon, because there are no available data to do any serious investigation on the Lagoon.

2.6.4 Fresh water inflow

The wide corridor of longitudinal density gradient extending from the river freshwater to the denser seawater is a main characteristic of many lagoons and estuaries. This gradient drives the gravitational circulation, which is characterised by a bi-directional flow, regarded as the basic flow pattern in a partially mixed estuary (Pritchard, 1952). The bi-directional flow consists of a surface current flowing seaward and a landward near-bottom flow. This type of non-tidal circulation is responsible for inducing stratification, competing against turbulent mixing generated by tidal currents to determine the vertical structure of the estuarine water column (Neves, 2010). Stratification can therefore be weakened or strengthened by turbulent mixing which, in turn, is controlled by the intensity of tidal currents. For example, one would expect weaker stratification during spring tides than during neap tide conditions, as the tidal currents are generally more intense during spring tide, causing the intensification of turbulent mixing.

The forcing exerted by tide and river flow on lagoon or estuarine gravitational circulation is therefore an important control on the transport of buoyant material within the system and also between the shallow water body and the adjacent coastal ocean.

2.6.5 Flushing, residence and mixing process in lagoon

Time scales that describe the mixing of estuarine and lagoon water are often used to characterize systems and to make general comparisons among them (Sheldon & Alber, 2006). Nomenclatures such as turnover time, flushing time, transit time, age, and residence time all describe different aspects of the rate of replacement of coastal shallow water bodies and dissolved constituents. There are various models or equations for quantifying these mixing time scales, some of which take different approaches to quantifying the same time scale. This variety of mixing time scales and equations, combined with overlapping terminology, has led to some confusion in literature (Sheldon & Alber, 2006). The transport time scales even though they are relevant to biological, hydrologic, and geochemical studies, was noted by Monsen *et al.* (2002) that the term was not consistently defined and applied with exactness in the literature.

In spite of the uncertainty in literature, a general estimate of the rate of replacement in shallow water systems can be useful for determining the sensitivity of a particular system to the introduction of pollutants. It could also be used as a standard against which evaluation rates of other processes in the system can be measured. Thus, systems that flush slowly can be expected to have different characteristics than those that flush quickly, especially with regard to the rate of inflow of freshwater and associated materials, such as nutrients and sediments, and the extent of within-lagoon processing of those materials.

In the North Atlantic for instance, the extent of nutrient retention within estuaries versus transport through them has been related to various measures of mixing time (Nixon *et al*., 1996; Sheldon & Alber, 2006). Hence, the growth rate of phytoplankton relative to the rate of physical flushing of water can determine if blooms are likely to occur (Howarth *et al*., 2000). A preliminary analysis shows that the longer residence time systems have high levels of chlorophyll and higher occurrences of nuisance/toxic bloom occurrences. In these types of systems, it is suggested that shellfish aquaculture could be used as an in-system management measure to complement traditional measures that limit nutrient inputs from the watershed (Bricker & Ferreira, 2008). To study the topology of a lagoon or estuary, the rate of water replacement in the system can be a good descriptor that may be used in such or study (Jay *et al*., 2000).

Characteristic mixing time scales are usually calculated for periods long enough to assume an overall steady state, so that simple equations with longer-term averaged variables may be employed. With any given model, inter-annual scale mean (or median) estimates are often built using typical values for a lagoon or an estuary, but if relevant conditions with the model can be defined for a shorter time period of interest (such as a season or sampling period), then mixing time scales specific to that period may also be calculated. The salt and water budgets for estuaries and lagoons which are basically developed for the Land-Ocean Interactions in the Coastal Zone (LOICZ) projects have used annual average or seasonal average values (Dupra *et al*., 2000; Gordon *et al*., 1996; Smith et al., 1999).

Budget models of any system are generally defined as mass balance calculations of specific variables (for example, water, sediment, carbon, nitrogen, phosphorus) for a defined geographic area and time period (for example, monthly, annual, or decadal) (Gordon *et al.*, 1996). The geographic extent of a coastal system budget can range from a particular coastal habitat to a semi-enclosed sea such as the lagoons, estuaries, Mediterranean Seas or to the global ocean. Any budget model should include all major sources and sinks around the system's watershed, both external and internal, as well as the dominant internal transformation processes for the variable(s) in question. For example, a carbon budget for a coastal bay should include delivery by freshwater, exchange at the seaward boundary, production-respiration, and sedimentation. The development of a budget usually requires a substantial amount of quantitative data for the geographic area in question. Although in some instances the lessons and experience of modelling can be transferred from one region to another with similar characteristics, most budgets usually consider only one variable for particular sites and this limits the ability to generalise model results between areas. Recently there has been a move to develop budgets that link several variables using known relationships (Gordon *et al.*, 1996), a good example is the building linked budgets using stoichiometric (quantities of reactants in a simple integral) relationships such as Redfield ratios (atomic ratio of carbon, nitrogen and phosphorus found in phytoplankton) (Atkinson & Smith, 1983; Cleveland & Liptzin, 2007). The use of known stoichiometric relationships allows linked budgets to be applied in new areas, with limited data availability in order to infer underlying fluxes.

In the LOICZ project, Bricker & Ferreira (2008) used the combination of Assessment of Estuarine Trophic Status (ASSETS) with models that simulate shellfish growth to predict water quality impacts of different shellfish growing scenarios in an aquaculture application. The resultant of the combined models provide a two dimensional application (device) for examining water quality impact. In one application, examination of the mass balance of nutrients within an oyster farm and analysis of related revenue sources indicated that about 100% extra income could be obtained by emissions trading, since shellfish farms are nutrient sinks. In the second case, the ASSETS indicators for chlorophyll and nuisance/toxic blooms are combined with hydrologic considerations to predict algal bloom occurrences. Since toxic algal species are typically slower growing, they are likely to be more prevalent in systems with longer residence times, such as lagoons. A preliminary analysis shows that the longer residence time systems have high levels of chlorophyll and higher occurrences of toxic bloom occurrences. In these types of systems, it is suggested that shellfish aquaculture could be used as an in-system management measure to complement traditional measures that mitigate nutrient inputs from the watershed. There is encouraging evidence in high use systems where aquaculture is prevalent such as Jiaozhou Bay, China, that the practice reduces the occurrence of algal related problems (Bricker & Ferreira, 2008).

Tidal flushing of the lagoon's water can occur by transporting material through the water current outside the limit of the inlets tidal excursion, with the help of tidal shear dispersion (Fischer *et al*., 2013), tidal rectification (Li & O'Donnell, 1997) and chaotic dispersion (Ridderinkhof & Zimmerman, 1992). On the other hand, several methods have been suggested to assess the exchange and transport processes between restricted zones and the ocean. A further instance of this is the method adopted by e Silva *et al.* (2014) to investigate tidal dispersion and flushing times in a multiple inlet lagoon. They choose to adopt the definition of flushing time (τ) of a time varying tracer concentration C (t) as suggested by Takeoka (1984) and a model based on the one used by Dias *et al.* (2009). Their results from the residence times calculated for 5-day windows around neap and spring tides show very low flushing times for both scenarios in the zones near all of the inlets. This suggests that around the zone of the inlets of any coastal system the water flushes quickly as a result of freshwater intrusion. Mixing or dispersion in tidal basins (especially lagoons and estuaries) is an extremely complicated process (Fischer *et al.*, 2013; Ridderinkhof & Zimmerman, 1992). It affects all biotic and abiotic substances dissolved or suspended in the water. In particular, it determines to a large extent the time scales of homogenization inside the basin and of the flushing of the adjacent continental shelf with external water masses (Ridderinkhof & Zimmerman, 1992). Conclusively, part of the stressors that influence the flushing time, residence time and mixing condition in the lagoon can as well be the rate of urbanisation of the coastal metropolitan city of the lagoon. A special consideration must be given to investigation of coastal urbanisation around coastal lagoons and estuaries for the purpose of creating a sustainable management scheme for the system, since human population is becoming increasingly high around the system.

2.7 Lagoon Sediment dynamics

A special consideration must be given to the sediment suspension in the lagoon system because of its functional importance to chemical, biological and engineering matters in the coastal zone (Bass *et al.,* 2002). Because of competitiveness for space and increase in other human activities around the coastal lagoons, it is believed that the sediment that is deposited in the lagoon through erosion or as a result of freshwater inflow varies over different timescale. Within any timescale (short or medium), the progressive change in the sediment structure in any lagoon is a function of the interactions between the natural processes, human involvement and the response of the physical characteristics of the shape, boundaries and content of the lagoon to such activities (Ferrarin *et al.,* 2016). As a result of non-linearity of the coastal sedimentary processes, it is difficult most times to forecast a large scale dynamic in the coastal lagoon sediment, hence, this limits future prediction of coastal sediment change (Ashton, Donnelly & Evans, 2008). It can also be noticed that the sediment evolution of the coastal lagoons and their wetlands are influenced sometimes by the sea-level rise (Carrasco *et al.,* 2016).

The comprehension of sediment dynamics in a complex environment like the coastal lagoons is very necessary for precise management of its ecosystems, regulation and mitigation of the impacts of human intervention (Ferrarin *et al.*, 2016). Unfortunately, it has not been very easy to carry out direct measurement of the sediment dynamics in the lagoons (Ferrarin *et al.*, 2016); such direct observation, if it can be done at all, will require a great effort which is not achievable most of the times. However, the complexity of the measurement of the lagoon sediment dynamics are as a result of factors such as tidal motion at inlet, longshore transport (De Swart & Zimmerman, 2009), complex number of processes occurring inside the lagoon basin, sediment suspension, depth and current refraction of waves, influence of tide (Bruneau *et al.,* 2011; Tambroni et al., 2010). Due to the complexity in measuring the sediment dynamics of the lagoon, various methods have been employed ranging from modelling to experimental. Amos *et al.* (2004) and Amos *et al.* (2010) investigated sediment dynamic process in the the Venice Lagoon using empirical method. The purpose of the 2004 experiment was to understand the mechanism controlling the stability of the lagoon bed types. The characteristic nature of its sediements revealed that summer erosion rates were lowered than that of winter, possibly as a result of change in water temperature. However, the 2010 experiment was basically measurement of sand transport at the inlet of the Lagoon using modified Helley-Smith sand traps equipment with 60-microns nets. Their result revealed that the movement of sediment that range from the very fine to fine sand is very contetious. Beach evolution in terms of the pattern of alternating erosoin and accretion observed alongshore by the sand barrier of the coastal lagoon can serve as an investigation measure of examining the the dynamics of lagoon sediment (Van Lancker *et al.,* 2004). Their experimental result indicate that strong current attached with the lagoon mouth bring about a high sediment mobility.

Other researchers (Bass *et al.*, 2002; Douillet et al., 2001; Lopes *et al.,* 2006; Lumborg & Pejrup, 2005) used model and simulation to examine the dynamic behaviour of sediment at the coastal environment. Model of sediment transport in any water body is commonly used as management tools for dredging in the lagoons and estuaries. Bass *et al*., (2002) used a model tool to study the behaviour of fine sediment suspension because of its importance to the coastal zone. Their model results show that transport of sediment accomplished with the use of the model is not sufficient enough future prediction, hence models rely on experimental approaches and the possibility of fitting it to previously acquired data. Basically, because of this reason, experimental approcah was used in this reaserch to investigate the dynamics of the Lagos Lagoon sediment.

Lagoons, even though have common characteristics across the global coast, notwithstanding have some peculiar local factors that can influence the variability in the pattern of their sediments. This was the concern of Manning & Bass (2006) in the study of variability of mud sediment settling under different tidal conditions. It can be deduced from their results that different tidal energy generated throughtout a tidal cycle have a distinct influence on the dynamics of the sediement in any lagoon or estuary. Further investigation by Manning *et al.,* (2010) using vidoe measurement to study flocculated sediment in the lakes and estuaries. The inference of their result suggest that at a higher depth, sediment floc population settles comparatively very slow, implication that the sediments will stay very long in the water column before it finally settles.

2.8 Uncontrolled Urban expansion and its influence on the coastal lagoon

Lagoons, estuaries and coastal seas have been the principal points of human settlement and marine resource that is used throughout history (Lotze *et al*., 2006). Hence, coastal urbanisation is rapidly expanding on a global scale, its impacts on seaward and landward communities remain poorly understood (Scherner *et al*., 2013). This is causing serious degradation of water quality (Lotze *et al.*, 2006) in most of the coastal ecosystems, especially in the coast environment of the developing nations. This is supported by Newton *et al.* (2003). They stated that:

“The quality of coastal waters in many regions of the world has deteriorated in recent years as human population and activities have increased along coastal regions. Urbanization is therefore one of the major issues that affect water quality and management of the coastal environment. ”

Terrestrial vegetation cover is gradually disappearing in a successive way and replaced with impermeable surfaces, such as tarmac and concrete (Yuan & Bauer, 2007), in conjunction with human population growth this has adversely increased the run-off of contaminated waters into coastal lagoons and the sea in general. Around the coast globally, almost 60% of the human population now lives within 100 km of the coasts (Lotze *et al.*, 2006; Vitousek *et al*., 1997). This is dreadfully affecting the oceans’ productive coastal verge (Halpern *et al*., 2008; Worm *et al*., 2006) and thus reducing the health status of marine coastal ecosystems (Halpern *et al*., 2012). The teaming human population around the coast has been a major factor for marine biodiversity losses and community shifts (Scherner *et al.*, 2013), these are among the resultant effects of coastal pollution. Hence, coastal ecosystems are under increasing stress from a variety of human activities that cause increase pollution, floral and faunal changes, and physical modification of the environment (Vitousek *et al.*, 1997). The changes by man to the coastal watershed have absolutely resulted in alteration of the ecology of aquatic systems. According to Bowen & Valiela (2001) as pressure for residential use of land increases around the coast very sharply, such increase demonstrates impact and extent of urban sprawl on the coastal watershed. This was corroborated by the statement of Ruiz-Luna & Berlanga-Robles (2003) which says that environmental stress always increases when a series of industrial activities like fishing, tourism and harbour are present at the same time around a coastal lagoon. The authors linked their findings about the condition around Mazatlan, northwest Mexico as associated with estuarine water bodies that have been continually modified. Bowen & Valiela (2001) reveal the implications that urbanization may bring into the management of coastal watersheds among which are lateral change on the land use mosaic and increased anthropogenic stress and besides this an increased nitrogen load where there is an increase number of industries.

A remote sensing method was used by Ruiz-Luna & Berlanga-Robles (2003) to assess land use, land cover and coastal lagoon surface reduction as associated with urban growth in northwest Mexico. The authors remark that population increases along with increase rural and urban activities, this directly affect the morphology of a lagoon, it does not only affect the status and availability of natural resources but also influence or induce incidental effects that must be evaluated from a regional view. Human activities include changes in the environment and this could be expressed as modification of the environmental landscape. In every coastal region, the magnitude of human activities and their effects are directly related to urban growth, this makes urban development a part of ecological system of any coastal area. Also, Ruiz-Luna & Berlanga-Robles (2003) noted that research on urban development as part of ecological systems is comparatively new and because of its inclusion of social and environmental interactions on different time and spatial scales, it was suggested that the ecosystems could be considered a different means of evaluating human influence on natural systems. Such huge human activities around the coast have caused some negative impacts such as disruption of sediment discharge, for example as in the closure of high Aswan dam and other series of responses that now threaten the northern Nile delta (Stanley & Warne, 1993). To develop an ecological model that can distinctively homogenise all dimensions of human impact is very difficult to come by, even though it is worthwhile, because the magnitude of changes from urban growth is variable and appears to be a complex variable of the local economy and the features of the landscape gradient (Grimm *et al*., 2000). With remote sensing image datasets, it is possible to assess the major transformations and to evaluate the trends of land-use changes around a coastal lagoon and also outline an adaptive management structure for the sustainability of the ecosystem.

2.9 Remote sensing method of studying changes in coastal lagoon area

Timely and accurate change detection of Earth surface is very important for understanding relationships and interactions between human and natural phenomena in order to promote sustainability, better decision making and management of any physical environment (Lu *et al*., 2004). Remote sensing is the art and science of collating information about an object or study location from a distance without making physical contact with the study location. This method is in many ways best to be applied to coastal lagoon investigation in some regions of the world because of high rate of insecurity especially in most African nations where there are oil prospects (Kuenzer *et al*., 2014). The authors applied the remote sensing method to investigate the land surface dynamic, they analysed data that spanned 1986 to 2013. In Africa as a whole, remote sensing method of study will be highly appreciated and be very attractive because of limited administrative capacity. This method of investigating a location without any physical contact could be very expensive to set up but it is safer, more economical and provides information that covers a large area of study. The basic principle behind the functionality of remote sensing is that a specific sensor is either attached to an aircraft or a satellite, and then it collects data by detecting the energy that is reflected from the Earth's surface. This principle of remote sensing has a wide range of applications in different fields of studies: coastal area, natural resource management, hazard assessment, and mapping.

In recent years, one of the most widely and important techniques for change detection that is finding a great usefulness in studying changes around coastal lagoon and its ecosystem is the remote sensing method with integration of geographic information system. Hence, this has been a very cost effective method and it is less time consuming.

Most of the factors that lead to the various changes around the coastal lagoon need to be identified and studied thoroughly, this will help to make a distinct general information classification of any coastal lagoon that is to be studied. However, such distinct classification will help to identify what are the basic factors that influence changes around the system. It will make it possible to plan a structured decision management that can easily be implemented.

The unique advancement in the design of sensors and methods of data analysis are making remote sensing more interesting and practical for studying and monitoring the impacts of anthropogenic and natural changes on coastal ecosystems (Klemas, 2010; Klemas, 2013).

2.10 Factors and antecedents of lagoon morphological changes

Several literature (Bowen & Valiela, 2001; de Noronha Vaz *et al*., 2012; Klemas, 2010; Kuleli *et al*., 2011; Scherner *et al.*, 2013; Serra, Pons & Saurí, 2008; STIVE, 2003; Xie *et al*., 2006) confirmed that coastal growth and changes around coastal ecosystems (the coastal wetland and the various landforms within) are as a result of natural factors and mostly human interference on quite different time related or spatial scales. The processes involved in the evolution of coastal lagoon processes and its records have been properly archived for some specific regions of the world, for example in the United Kingdom (Lario *et al*., 2002; Long *et al*., 1996), Portugal (Dinis *et al*., 2006; Granja *et al*., 2010; Pérez-Ruzafa, Marcos & Pérez-Ruzafa, 2012), and the Canterbury region in New Zealand (Kirk, 1991; Soons *et al*., 1997).

From literature, two major factors bring about the coastal lagoon morphological changes, these are, natural factors and increased human activities. If the natural ecological condition of a lagoon and its ecosystem can be preserved without being disturbed by any human influence, changes may take place in the system over a long time scale, such may not be easily noticeable and may not quickly aggravate to serious degradation. Therefore the factors and antecedent conditions causing changes in the lagoon could be discussed in two ways: natural factors and influence of human activities. First, under natural factors, higher river flows from the upland (Lam *et al.*, 2008) could cause change in the lagoon circulation and result in a high volume of sediment delivery to the coastal zone contributing to the littoral drift which can temporarily be stored in sand-spit along the coastal down-drift (Kirk, 1991). Constant re-occurring of this has the potential to increase sand deposition hence gradual reduction of the lagoon inlet mouth, thus flooding that could lead to eventual closure of the mouth and coastal erosion could be resulted. One of the major natural factors that influence changes in the morphology of the lagoon system is sea level rise (Lopes *et al*., 2013; Nicholls & Cazenave, 2010; Nicholls *et al*., 2007), this will be discussed very well in section 2.11. In the tropic region where the prevailing climate condition is wet and dry season, more sediment from upland is transported as a result of high intensity of rainfall rate (Sharma *et al*., 1994) and the sparse vegetation cover due to high rate of human infringement on the coastal ecosystem (Pilgrim *et al*., 1988). During raining seasons the inlets are river dominated, hence river floods reorient the channels and more sediment is exported from the upland into the lagoon. However, during the dry seasons, the tidal inlets are wave dominated and act as sediment sinks, sediment that settles along the lagoon sand-spit could be gradually eroded away during raining season by high volume of erosion from upland without much replacement. This episodic alternation in river flow, sediment transport and wave climate make the lagoon inlet morphology to be seasonally varying and highly dynamic (Lam *et al.*, 2008)

Secondly, in the recent time as a result of economic value derived from the coastal zone, global population has increased around the coasts; thus urbanisation of the large cities and human activities around the coast has greatly increased. Since 2007, the coastal population has increased with more than 600 million people living in the low lying coastal areas (McGranahan *et al*., 2007). No doubt increased urbanisation and anthropogenic activities around the coast have contributed to increased climate change, hence an eventual rise in sea level which has put a lot of people and the coastal lagoons at high risks. Increase activities around the coast due to increase urbanisation has induce change in the coastal ecosystem, coastal lagoons inclusive, and is causing seaward hazards threat (McGranahan *et al*., 2007). Apart from vulnerability to seaward hazards, the dense population of human settlement around the coast becomes an overburden on the lagoon ecosystems or the entire coastal ecosystems, many coasts are already under severe pressure as a result of this, especially in the developing countries where urban development planning is at low ebb. Regardless of the nature of changing geographic patterns in human settlement and urban development with the impact they induce on coastal environmental conditions, urbanisation has always been investigated historically regardless of its spatial relationship with the coastal environmental condition (McGranahan *et al*., 2005). This concern was supported by Small & Nicholls (2003), when the authors reflected on the accounts that "previous studies with moderate-resolution spatial data had always shown that, historically, most populations preferred to live within 100 km of coasts and near major rivers", this has no scientific data to back it up, hence this must be investigated to confirm the prove.

Systematic investigation of urban region limited to a small belt of coastal area, especially those prone to risk as a result of climate change is the concern of McGranahan *et al*. (2005) in their study. Distribution of population and settlement of size in the low laying coastal zone strongly determines how and the rate at which an environment is affected, such effect always causes a direct alteration on the configuration of its landscape. Vulnerability increases strongly in countries especially with large populations in the low elevation region, like the coasts of countries like China and Bangladesh. One of the major effects of large population in the coastal area is the struggle for space both for human settlement and for citing of industries nearer to the seaport. This has increased proportionally around the coastal lagoon as human population increases. Hence, part of the lagoon water is reclaimed in most of the coastal urban cities and turned to land for urban expansion and development.

Several socio-ecological pressures (increase in population, increase in coastal industries and conversion of natural ecosystem to settlement area) are common around coastal lagoons and other coastal systems because of the prevalent incessant increase in human population (Kuenzer *et al.*, 2014). The greatest of them is environmental pollution due to illegal discharge of industrial effluent as well as other toxic substances to the lagoon as the last deposit resort. High and frequent rate of flooding during raining season in the tropic region exasperates the flow of industrial waste into the lagoon and increase the pollution threats. Large amount of sediments that are rich in heavy metals such as Pb, Zn, Fe, Hg contaminate the lagoon aquatic habitat and affect the surrounding farmland (Achudume, 2007). These effects of industrial effluence and sediment flow for industries from upland in metropolitan city around the coastal lagoon are becoming visible in Lagos Lagoon. During the data campaign (in April, October, November and December 2014) carried out for the present research, the main artificial channel that feeds the Lagoon industrial with waste is becoming inaccessible due to sediment deposition. More than 3km from the channel's mouth into the Lagoon had been filled with muddy of sediment; this was not the case some years back.

In addition to immediate effects as a result of increased human activities, increasing population will cause increase atmospheric temperature, hence global warming will be one of the results and this will have a serious long-term effect on coastal ecosystem such as submerged coastal vegetation and habitat degradation and destruction due to sea level rise (Titus *et al*., 2009). This is supported by the investigation done on the coasts of USA from 1998 to 2004 by Dahl (2005) where the author proved that by 2004 13,450 hectares of the coast had already been lost.

The impact of uncontrolled population and human activities on the changes in coastal lagoon systems is of huge consequence; this always results in degradation, deterioration, loss of aquatic wealth and coastal landscape, the trend has increased drastically over some years and will continue to do so especially in the developing nations (Lasserre & Campostrini, 2007). The lagoon morphology is susceptible to changes depending on the population that settles around its coast. The higher the population, the higher the stress encounter by the system. As population of coastal dwellers increases yearly, coastal lagoon sustainability issue must be given serious attention to avert unbearable coastal hazard that cannot be cope with. If proper mitigation plan is put in place around all the coastal lagoons globally, equilibrium will be maintained between the natural ecosystem of the coast and the human activities around the zone.

The emergence of marine spatial planning in developed nation like United Kingdom has gone a long way to help with the consideration of fundamental human activities and associated spatial coastal space has helped in offshore and coastal spatial planning and management evolution (Smith et al., 2012). However, it is noteworthy to understand that the system of land-use planning in any coastal state impacts intense influence on its coastal waters due to the repercussions of land allocations and increased urbanisation on the adjoining marine environment (Smith *et al.,* 2011). In contrast to the submission of Smith *et al.* (2011 and 2012) on coastal spatial planning and management, lack of diligent spatial planning with consideration on land mass and population growth rate in the coastal zone of Lagos Nigeria has brought uncontrolled deteriorating situations to the region, hence a need to investigate and assess the changes that has been impacted morphologically and hydrodynamic wise.

2.11 Effects of the climate change on the coastal lagoons

Shallow coastal lagoons are economically important in terms of land use and urbanization (Brito *et al*., 2012); biologically it is a productive zone for coastal ecosystem habitats (Nixon & Buckley, 2002) and home of aquatic plant biomass (Garcia *et al*., 2001; McGlathery *et al*., 2007), these are true in all the coastal area where lagoons exist. In Europe, most populated cities are found within the confinement of the coasts and in most cases the lagoons or estuaries situated near such coast are often affected by human activities through discharge of industrial wastes and other contaminations from urban settlements areas. If the system is economically, socially and biologically valuable, when considering the global challenge of climate change, how will the shallow coastal lagoons respond and cope with this global trend in climate change? This concern led Brito *et al.* (2012) to a model investigation of the common response of the shallow lagoons to the rising climate change. The authors noted two major important factors that could cause immediate and noticeable change in the coastal lagoon as shallow depth and its submergence of photosynthetically active organisms (that is organisms in an ecosystem that produces biomass from inorganic substances).

dCSTT model was used by Brito *et al*., (2011) to study the prospective response of Patos lagoon to climate change. The scenario considered in their model was a global climate change that could result from sea level rise due to global warming, hence the model simulated temperature and was combined with effect of light to investigate the reaction of shallow lagoon to climate change. The result of their investigation shows that the water column was relatively similar throughout the years of investigation while chlorophyll concentration varies. This is an indication that very high percentage of benthic chlorophyll correspond to the chlorophyll of the system. The model shows that a sea level rise is likely to be responsible for weakness of light in water column because of radiation weakness in water. Hence the more volume of water due to sea level rises that intrude an area the weaker the light penetration in the water column (Lloret *et al*., 2008).

Moreover, due to increased urbanization around the coastal lagoon and global climate change, the system eutrophication as a transition space between land and sea is likely to be worse (Lloret *et al*., 2008). Many studies in the past warn on the effect that eutrophication processes bring on the coastal zones and lagoon in particular, but the influence that both eutrophication and climate change will produce has not been seriously examined by many papers. Only few studies have examined in detail the susceptibility of coastal lagoons and coastal zones taking into consideration the global climate change (Harley *et al*., 2006; Jimenez & Sanchez-Arcilla, 1997; Nicholls & Hoozemans, 1996; Nicholls *et al*., 1999; Nicholls *et al.,* 2007; Sánchez-Arcilla *et al*., 1996; Sanchez-Arcilla & Jimenez, 1997; Sánchez-Arcilla *et al*., 2008; Short & Neckles, 1999; Simas *et al.,* 2001), these are the few authors that have given this particular topic of investigation the maximum attention to understand what exactly will be the outcome of the combined effect of eutrophication and climate change on any coastal lagoon and generally the coastal zone. Furthermore, to understand and identify the future possibilities and implications of the processes of climate change and increasing coastal eutrophication on the sensitive transition medium (lagoons) between the sea and the land, there is need to understand the integrations and interactions of both processes (Lloret *et al*., 2008). It will enhance result oriented planning and management of the coastal lagoon ecosystem, thus disintegration and gradual collapse of the system will be avoided.

One approach that has been developed in the recent time to examine the possibilities for coastal changes is the Coastal Vulnerability Index (CVI) (Alexandrakis *et al*., 2010; Gornitz, 1990; Thieler & Hammar-Klose, 1999). The CVI is a simple and functional approach developed to approximate the subjection to coastal retreat of any coastal area relative to sea level rise. The approach has been used by United State Geological Survey (USGS) at national scale to evaluate the possible vulnerability of the country's coastline and in more detail for the U.S. National Park Service (Thieler & Hammar-Klose, 1999). The USGS used six variables that are best considered for evaluating the susceptibility of the shoreline to the rise in sea level, these variables are – coastline landscape (slope), geomorphology, shoreline change, relative sea-level change, mean significant wave and mean tidal range (Thieler & Hammar-Klose, 1999). The subject of global climate change is becoming more enormous and the effect more pronounced on our coasts. Sea level rise is becoming wide and challenging as the subject of climate change, the effect has been very visible on the coast. The influence of this on coastal lagoon is discussed in section 2.12.

2.12 The response of coastal lagoon to Sea Level Rise (SLR)

Research on climate change has revealed that globally the sea level is rising at an increasing / accelerated rate (Church & White, 2006; Church & White, 2011; Nicholls *et al.,* 1999; Rahmstorf, 2007), the rate during the twentieth century is on the average of 1.7 ± 0.3mm/year (Church & White, 2006). The extent to which the climate induced sea level rise could affect the coast remains uncertain and brings great concern to the coastal scientists as further accelerated increases in the sea level rise cannot be ruled out throughout the twenty-first century (Nicholls *et al*., 2011). Studies have shown that the plausible reason and major driver for incessant rise in the level of the sea water is the increase in the concentration of the atmospheric abundance of Greenhouse Gaseous emissions and aerosols, this increase the atmospheric temperature and sea surface temperature hence, the energy balance of the climate system is changed between the solar radiation and the land surface (Change, 2007; Titus & Anderson, 2009). The growing population of people with increasing resources around the coastal areas increases the Greenhouse effect hence, increase in global temperature and melting of the glacier ice (Nicholls *et al.*, 2011). How much of the glacier ice sheets from the polar ends of the globe are melting into the sea is the biggest uncertainty that is being confronted (Nicholls *et al.*, 2011). However, in the last century, the rate of global sea level was estimated as 1.7mm/year but with the emergence of satellite observations, more reliable sea level data with global coverage are available and these show that global sea level has been rising by 3mm/year (Change, 2007). The Third Assessment Report (TAR) of IPCC reveals that sea level rise was estimated to be 2.2mm/year +/- 0.8 (Change, 2001). The TAR listed estimated sea level rise that were acquired on a global scale.

The fourth Intergovernmental Plan on Climate Change (IPCC) report (AR4) projected the estimate of sea level rise for this century that it could likely range from 18cm to 59cm (Change, 2007). However the estimation of IPCC's AR4 did not include the contributions from Greenland and Antarctica (Titus & Anderson, 2009). Basically the actual rise may be higher or lower than the projection of IPCC. Hence there is uncertainty in the estimation of sea level rise; this dilemma in the rise projection could be as a result of variation in the Greenhouse gas both now and in the future. Apart from this, the global sea level temperature has been confirmed to be increasing which support the fact that more glacier ice will be melting due to rise in temperature therefore an increase in the sea level will be the outcome. Climate model of IPCC 2001 report indicates spontaneous rise in the annual global mean temperatures (Change, 2001; Nicholls *et al.*, 2011).

Severe consequences could be the result of unchecked incessant negative change in the climate condition especially that of the sea level rises. The unresolved and unabated impact of rise in the sea level is considered to likely have a severe risk of displacing up to 2.4% of the world population (187 million people) by the end of twenty first century (Nicholls *et al.*, 2011), greater percentage of this population are living around the coastal zone. Sea level is raised by warmer temperature which melt the glacier ice sheets, the melted ice sheet is discharged into the ocean this in turn increase and expand the volume of the ocean water which split into the enclosed water bodies like the lagoons and the estuaries and increase the water level in the systems (Titus & Anderson, 2009). The effect of increasing sea level brings negative hazards for coastal areas, including: increased erosion, increased flooding/submergence, increased salinisation, threats to coastal cities in terms of storm surges, all these could create direct negative impact on the urban coastal communities, wetlands, coastal ecosystem and the various infrastructural development around the coast (McInnes *et al*., 2003; Morris *et al*., 2002; Nicholls & Cazenave, 2010; Titus *et al*., 1991). Due to the negative effect of sea level rise, scientists and coastal policy makers face the challenge of understanding how the sea level rise will affect the coastal area and the best management plan that can enhance sustainability (Nicholls *et al*., 1999). If the sea level rise proceeds at the present rate, it may lead to submergence of most of the coastal lagoons turning it to part of the ocean.

2.13 Theory in remote sensing and method for land cover in lagoon ecosystem

An overarching question in investigating and detecting changes around coastal lagoons, is whether satellite images, in particular Landsat images, can be used as a tool and is it possible to use a remote sensing method to detect morphological changes around the coastal lagoon? The use of satellite image for change detection is based on seasonal and multi annual time scale approach to evaluate this method as a tool for monitoring the rate of urban development. However, a possible answer for the question whether remote sensing method and satellite images can be used as a means of detecting changes in coastal lagoon ecosystem could be found by simply exploring a range of assessment approaches using remote sensing data.

2.14 Background in remote sensing – atmosphere, scattering and satellite sensitivity

Several bands of wavelengths abound in the electromagnetic radiation (EMR) spectrum which is possible to be separated. From the overall spectrum of EMR, only few of the wavelengths are important for use in remote sensing (Raup *et al.*, 2007), these are positioned between the ultraviolet radiation and medium infrared spectrum which is the microwave spectrum; this is the medium that is interesting to remote sensing. The basic mechanism behind the technique is that EMR from a source (artificial or natural) passes through the atmosphere (this contains several gaseous substance) to a sensor on earth. Part of the EMR while passing through the atmosphere are either absorbed or scattered as a result of the presence of different atmospheric gaseous layers (O_2, O_3, CO_2, N_2O and H_2O), the transmissive pattern of the atmosphere is summarised in Figure 2.12 (Paul *et al.*, 2004; Raup *et al.*, 2007) based on three ranges Visible Near Infrared (VNIR), Short Wave Infrared (SWIR) and Thermal Infrared (TIR).

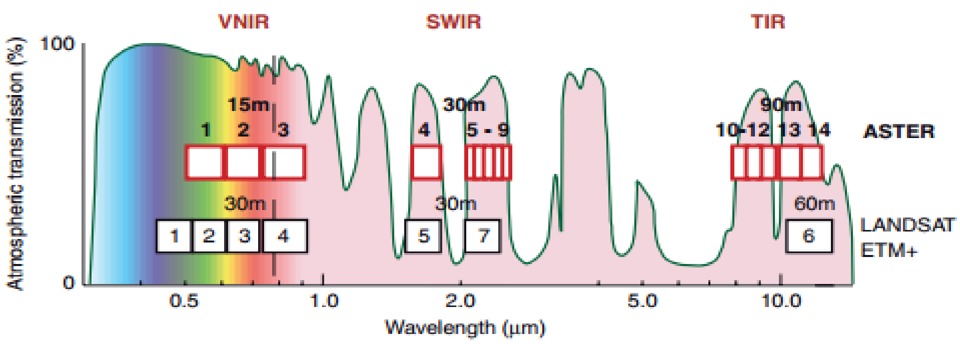


Figure 2.12: Atmospheric transmission, location and spectral bands of ASTER and Landsat ETM - Adapted from Raup *et al* (2007)

In remote sensing technique it is feasible to presume that the EMR spectrum transmits information relating to the properties of an object to be studied to a sensor, and that the same information is recorded and transformed to a useful image (Paul *et al*., 2004).

2.15 Summary

The extensive literature that was addressed in the research gives a body of comprehensive knowledge about coastal lagoons and the changes related to it in morphologic and hydrodynamic terms. This section has successfully collated the definition, common global characteristics, and different classification of coastal lagoons. However, coastal lagoons and estuaries, were contrasted to identify their distinctiveness because of their close characteristics. This will help coastal scientists to have unbiased focus especially for such coastal landforms that are closely related. The section also reviews sediment, morphologic and lagoon water dynamics to see what methods have been adopted and the results achieved.

Remote sensing methods were reviewed and considered one of those that will be very efficient and effective for a region like Nigeria where there is serious security problem.

2.16 Conclusion

Conclusively, a lagoon is a coastal feature and they are spatially distributed all across the world's coastal zones. Some lagoons might be mistaken for estuaries because of the close inter-relationship between these two costal features. Interestingly, the prevailing dominated factors (wave or tide) around the system enable the scientist to more easily distinguish a lagoon from an estuary. Lagoons are wave-dominated coastal landforms while estuaries are tide-dominated.

Additionally, from the various literatures that have been reviewed in this study, to the best of the author's knowledge, it is apparent that a greater depth of research has been conducted on estuarial environments than coastal lagoons. This could be as a result of lagoon tending to be shallower than the estuaries, hence it is possibly more easy and convenient to gain passage and navigate through estuaries for data collection with dedicated research vessels that are usually equipped with arrays of instrumentation and sensors that are easier to deploy in deeper estuarine waters. This is one of the challenges that were faced during the data collection for this research.

Although lack of sufficient data seems to be a general issue with the studies on a lagoon, some researchers embark on the use of numerical models to carry out hydrodynamic studies on parts of a lagoon that are considered for studied and simulate a scenario of the changes on the system. The results of such studies can sometimes help with management decisions for the sustainability of a lagoon being studied. However, morphological investigations on different types of lagoons can suffer setbacks, as it is not a simple or trivial task to adapt an estuarine hydrodynamic model for use in a shallow lagoon aquatic environment. Hence, this window (i.e. lagoon morphological studies) is widely open for scientists to explore, especially at this time of incessant urban expansion, and increase in stresses arising from continually developing human activities in the coastal zone and around lagoons.

CHAPTER THREE
RESEARCH METHODOLOGICAL APPROACH AND DESIGN

3.1 Introduction

This chapter presents the methodology and the procedures adopted to obtain the required results and fulfil the aim and objectives of the research. The section discusses the specific details about the research stages (preliminary study; method of data collection, design, and modelling; long-time study and demonstration of transferability), type of data used and their time scale with dates, and processing of the research data. The various methods and approaches employed for solving the different components of the research are considered explicitly; this comprises the approach of using satellite images, bathymetry and in-situ hydrodynamic data to investigate evolution on the Lagos Lagoon with a focus on observation and inference of change on the morphodynamics of the Lagoon. Lastly, a brief clarity on the scope and limitation of the methodology adopted in the research is discussed.

The main stages of the research methodology adopted are presented in Figure 3.1. As shown in the Figure, the research was completed in three stages; these are discussed in sections 3.5 to 3.7 below. This research considers morphodynamic changes in the Lagos Lagoon with the aim of employing functional mechanisms and developing models to evaluate and analyse the changes in the lagoon. The research is not about proposing an isolated model and mechanisms but rather to investigate hydrodynamic and morphology changes using empirical data that was collected during the period of the research. The data was analysed and inferences of change were drawn as conclusion.

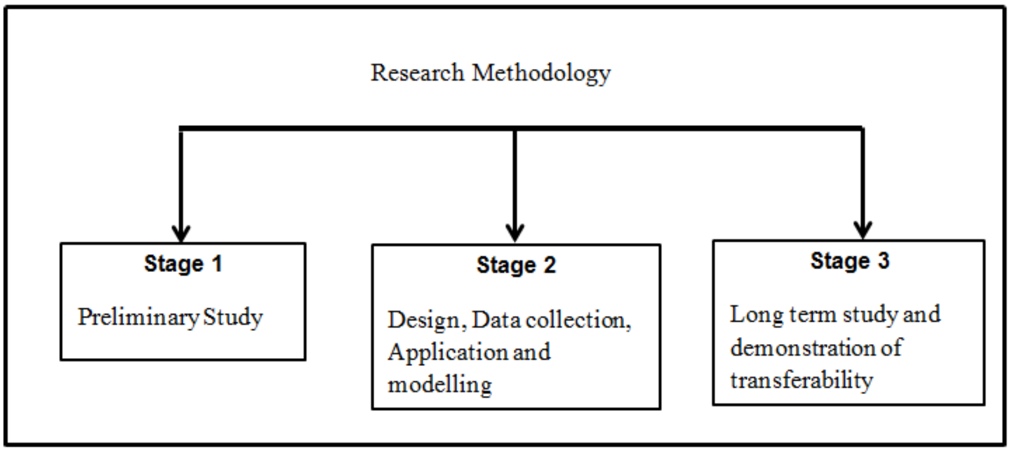


Figure 3.1: Research methodology, showing three stages of the work

3.2 Aim and objectives of the chapter

This chapter is very significant to the research work, as it conveys the primary approach used in carrying out the research. The main aim of the research method is to design a functional mechanism with an empirical data collection method through which the morphological and hydrodynamic changes in the Lagos Lagoon could be evaluated and analysed. The objectives of the chapter are to determine methods of testing measurable parameters and to produce a framework of attainable and relevant design structure for the study.

3.3 Methodological approach and design

Various studies have identified different methodological approaches to undergo research. Prominent among such approaches includes quantitative approaches (Brannen, 2005; Bryman, 2006), qualitative approaches (Denzin & Lincoln, 2009) and newly developed mixed method approaches by Creswell (2013) and Creswell & Clark (2007). This research adopts the mixed method approach (Cameron, 2011; Denscombe, 2008; Johnson *et al.,* 2007) because of its logical assumptions in the sense that the mode of enquiry is steady, transformative and simultaneous. The mixed method involves the use of both qualitative and quantitative data and analysis. In this research, varieties of methods are used at different stages in the process to reasonably build and strengthen the effectiveness of the research results.

3.4 Research Stages

This study is divided into three different stages. The stages include data collected from the Lagoon, the various results from the field data and the changes that could be inferred from the various results considering the indicators or forcing responsible for the Lagoon dynamics. This was done using field data collected on two different seasons on the Lagoon and satellite imagery to obtain information regarding hydrodynamic and morphological changes in the Lagoon. A Geographic Information System (GIS) was used to assess aspects of the spatial dataset collected from the Lagoon system to analyse the impact of the changes on the Lagoon.

The main objective of this study is to establish the progressive changes that take place in two perspectives (hydrodynamics and morphological). This creates a platform to ascertain a coastal barometer for measuring the impacts of climate change and human activities around the coastal Lagoon and it will stand as a gauge to know how coastal dwellers and partnerships are preparing for any sudden consequences of natural hazards that might severely impact the Lagoon. However, even though an intense study of the high rate of increased morphological changes due to increase coastal urbanization around the coastal lagoons in developing nations has not been thoroughly looked into, it is recognised that in the near future efficient and sustainable management plans (long and short term) for the coast are one of the basic adaptation measures that will be highly needed in the event of climate change challenges that is affecting the global coast. The breakdown of the stages involved in this study is discussed in sections 3.5 to 3.7.

3.5 Stage One: Preliminary study

The preliminary study includes the literature review in order to explore the body of knowledge and previous research work conducted on both hydrodynamic and morphological changes in the coastal lagoons. This stage included a visit to the Lagos Lagoon in Nigeria to do a preliminary investigation on how to carry out data collection for the research; it also involved data quality and data assessment, understanding of the relevant software and the development of skills needed for the research. Also, the necessary primary and secondary data such as maps, satellite images, and field data were acquired and processed. However, as is the custom of any research project, the setting of SMART (This stands for Specific, Measurable, Attainable, Relevant and Timely) objectives is essential and plays an important role to the successful completion of such research. Therefore, as a proper management approach, a work plan (Gantt chart) showing the research stages and timeline was developed to monitor how the research would be run, its development and its progress. A full description of stage 1 components – preliminary stage is discussed below.

3.5.1 Literature Review

A broad and extensive review of the literature on morphological and hydrodynamic changes in lagoon systems was explored in order to gain relevant and current knowledge of the forcing that causes morphological and hydrodynamic changes to the Lagoon as well as the monitoring and management issues. In particular, a comprehensive review of the previous studies on the different methods applied for monitoring hydrodynamic and morphological changes in estuaries and lagoons with a view to improving its sustainability indices were examined. Several researches have been carried out on lagoons globally that involve changes in sediment flux, morphodynamic of intertidal lagoons, salt intrusion and changes to the lagoon inlets due to wave actions.

Thereafter, the study review was focused on the current and potential methodologies for investigating hydrodynamic and morphological changes in Lagos Lagoon and the parallels with other lagoons; this is used as a building block for formulating the research.

3.5.2 System and equipment familiarisation

As part of the preliminary study, a visit was made to the Brunel Laboratory of Plymouth University to gain familiarisation with both field and processing activities for the use of the current meter -the principal instrument used during the research data collection. Another two full days were devoted on the boat (Falcon Spirit) with other research students for a demonstration on how to use the current meter for deployment and data collection. Furthermore, a hands-on demonstration of the equipment was carried out by one of the Technologists of Marine Science School, Plymouth University both in the office and in Plymouth Sound before embarking on the use of the equipment in Nigeria for the research data collection. The exercise was relevant for the research data collection period. The calibration of the equipment is very important to ensure instrument accuracy; consistency and reliability were ensured by multiple uses and checking on the process and results.

3.5.3 Preliminary Data Acquisition

To have a better understanding of the study location with the research supervisory team, two major preliminary data were collected about the Lagos Lagoon. The first was a Google Earth (Landsat 7) image of the area which gives the geographic location of the Lagoon in Nigeria. The image also depicts the urban developments as it surrounded the Lagoon in 2012 (see Figure 3.2). A significant development can be seen at the western part of the Lagoon. The southern portion of the system is already saturated with development to the extreme verge of the Atlantic Ocean. Secondly, other preliminary data that was used to do a preliminary study of the Lagoon were the small scale chart (Figure 3.3) of the Lagoon, collected from the United Kingdom Hydrographic Office (UKHO), Taunton, United Kingdom. The research supervisory team examined the charts that were collected from UKHO, but determined the scale was too small; this made it inappropriate for the actual research study but it was helpful for the preliminary study. Even though the charts could not suitable for use in the research because it was acquired on small scale due to this many information that will be needed to explore the study area might be missing. However, historical information was gathered from the hydrographic charts which help to understand the historical trend of changes that has taken place inside and around the Lagoon for over one hundred years. Contrasting Figure 3.2 and Figure 3.3, high rates of urban development has been witnessed between 1863 to the present; no wonder the estimated population of Lagos is predicted to be 17 million people living around the Lagoon.

Figure 3.2: Image depicting Lagos Lagoon with urban settlement (©Google Earth, 2016) where the blue is the Atlantic Ocean, the light grey is urbanised and the green is largely undeveloped

Figure 3.3: Lagos Lagoon, 1863 - what can be seen regarding Lagos Lagoon as far back 19th century from UKHO Archive, (UKHO, 2013)

3.5.4 Data requirement

Available data on the Lagoon was examined, Table 3.1 summarises the available data that could be accessed about the Lagos Lagoon. One major issue was that there was no previous openly available data on parameters like salinity, temperature, density and speed of sound which are part of the basic data required for the research. Bathymetric data was another data needed for the study; contact was made with several organisations such as Nigeria Hydrographic Society, research institutions and Ministry of Land and Survey but there was no positive result from them. Concerted efforts were made to contact the authorities of the school of oceanography in Lagos Nigeria which it was expected should have several years of data that fit into this study; no good response was received from them. From the investigation made, the only bathymetric data that was available was that of 2012 (just one epoch). This is strictly under the watch of the Lagos state government and was not released even for research purpose but the Department of Surveying and Geoinformatics, University of Lagos was privilege to have it in their custody, and this gave the opportunity to have the data. The multinational companies in the oil and gas sector that have their commercial offices at the Harbour (around the lagoon outlet to the sea) would have been a good source to get a wealth of relevant data about the system, but since they have no business with the Lagoon they have no data on it. The first challenge of this research was how to get appropriate data to accomplish the study.

Table 3.1: Summary of data availability and acquisition for Lagos Lagoon

Data Source	Coverage	Epoch	Purpose	Availability status	Remarks
Bathy data from University of Lagos	Entire Lagoon	1	Depth investigation	Available	Access granted
Landsat image	Entire Lagoon	5	Land use land cover	Available	Access granted
Google image	Entire Lagoon	1	Coastline delineation	Available	Access granted
Current meter data	Study on part of the Lagoon	1	Hydrodynamic study	Not available	To be collected on the lagoon

3.5.5 Data Availability/Data Type

Following the preliminary study and the consultations made to different organisations in Nigeria, it was ascertained that no hydrodynamic investigation has been carried out on Lagos Lagoon; hence there is no data in that area. Also, data that reveals changes in the morphology of the Lagoon could not be found. The choice of data for the study was based on cost of acquisition, available instruments and proximity to a processing laboratory. Hence, three distinct data types (bathymetry, satellite and in-situ hydrodynamic data) were embarked upon to accomplish this research through primary and secondary sources. Table 3.2 shows the summary of the data type with their sources, ranges and time/space.

Bathymetric data

Two epochs of bathymetric data were used for the investigation of the changes on the Lagoon water bed - these were acquired in 2008 and 2014. The 2008 bathymetric data was collected from the Department of Surveying and Geoinformatics, University of

Lagos while 2014 data was acquired by the author on the Lagoon during the 2014 data collection for the research.

Satellite data

Due to the cost of acquisition, Landsat satellite images from 1984 to 2016 were used to investigate the morphological changes in the Lagoon ecosystem and its coastline. There are images of better resolution than Landsat image but the cost of acquiring this is beyond what the research funding can afford. Two major challenges were encountered with the use of Landsat imagery: first is the challenge of cloud cover - the majority of the acquired Landsat satellite images that cover the study area have cloud cover problems; secondly, Landsat images are not available prior to 1984.

In-situ hydrodynamic data

Empirical hydrodynamic data was collected in 2014 during the dry and wet seasons to cover the two seasonal weather conditions. A Vale port current meter was used in collection of the in-situ hydrodynamic data which comprises salinity, density, depth, speed, direction, temperature, conductivity and speed of sound.

Secondary data

Secondary data were mainly data collected from organisations and those derived from the primary data source, these comprise of rainfall data, population, Richardson number, and the LST, NDVI and coverage area of mangrove, swamp, built area, vegetation and bare land which were generated from the in-situ hydrodynamic data and the Landsat image data respectively.

Table 3.2: Table showing the research data types, their sources, time and extent of coverage

Data Type	Name of data	Sources	Time/Space	Data Coverage
Satellite	Landsat 4	USGS	1984 - 1986	The Lagoon and its ecosystem
Satellite	Landsat 5 TM	USGS	1990	The Lagoon and its ecosystem
Satellite	Landsat 7 ETM+	USGS	2006	The Lagoon and its ecosystem
Satellite	Landsat 7 ETM	USGS	2002, 2014, 2015	The Lagoon and its ecosystem
Satellite	Landsat 8	USGS	2016	The Lagoon and its entire coastline
Field data	Bathymetry	University of Lagos, Nigeria	2008	Entire Lagoon
Field data	Bathymetry	Collected on the Lagos Lagoon	2014	Half of the Lagoon (covers western region to mid-region)
In-situ hydrodynamic data	Salinity, density, depth, temperature, conductivity, speed, coordinates of points,	Collected on the Lagos Lagoon	Dry season 2014 and wet season 2014	Entire west region to the mid-region
Demographic data	Population of Lagos State	National Population Commission of Nigeria, Lagos branch	1963, 1991 and 2006	Entire Lagos State
Meteorological data	Rainfall, air temperature and relative humidity	NMA, Lagos	1963, 1991 and 2006	Entire study site
Derived data	Richardson number,	In-situ hydrodynamic data	Dry and wet season 2014	Entire west region to the mid-region
Derived data	predicted population	From acquired population data		Entire Lagos State
Derived data	NDVI and LST	From satellite data	1984 – 2016	The Lagoon and its ecosystem
Derived data	Coverage area of swamp, mangrove, built area, vegetation and bare land	From satellite data	1984 - 2016	The Lagoon and its ecosystem

3.5.6 Data Limitation

Robust investigation of the Lagoon bottom configuration was very difficult because there were no available repeated bathymetric data on the Lagoon to carry out such investigation. This prompted the ideal of collecting bathymetric data during data collection on the Lagoon to join the 2012 data collected from University of Lagos to assess the changes on Lagoon bottom configuration within the period of data coverage.

If enough historical bathymetric data had been available, it would have helped address any seasonal spatial changes that take place in the Lagoon in terms of siltation and erosion. However, bathymetric data was collected during data campaign (2014) this was used with the 2008 bathymetric data collected from the University of Lagos to analyse the change on the Lagoon bottom configuration in terms of accretion and erosion.

3.5.7 Proposition

Following identification of the data available and having acquired them, consideration was given to the methods for implementing analysis of the Lagoon hydrodynamic and morphological changes.

3.6 Stage Two – Method of data collection, design, application and modelling

The data used for the research (Section 3.5.5) includes: satellite Google image (Google Corporation N.D 2006), Landsat satellite image and on site field data collected with the use of a current meter. There are two components for the satellite image used; the first one is the satellite Google image for coastal delineation of the Lagoon. To ascertain the entire coverage of the Lagoon, the Google image was zoomed in to get sufficient resolution and then joined consecutive images together to form a complete singular map of the Lagoon and its catchment area. This image was georeferenced and the coastline digitised to depict the extent of water coverage in the Lagoon ecosystem. This was used as a reference base map to compare the morphological changes around the Lagoon from when clear satellite was available over the study area. Secondly, data needed for investigating the Lagoon's morphological changes are mainly Landsat satellite images. The images were acquired from the United States Geological Survey (USGS) site (http://earthexplorer.usgs.gov); accessing the data on this site is free for research purposes. The archive of the Landsat images contains varying and very large volumes of data (see Table 3.3); it contained approximately 1000 Terabytes of data in 2008 (Wulder *et al.,* 2008). The data covers the entire globe.

Table 3.3: Summary of National Satellite remote sensing Landsat data archive (Wulder *et al.*, 2008)

Sensor	Records	Dates	Volume
Landsat MSS	649,412	1972 – 1992	19TB
Landsat TM	692,556	1989 – Present	347 TB[2]
Landsat ETM+	704,770	1999 – Present	654 TB[3]
The USGS EROS data store was queried on March 27, 2007 The volume of TM data is estimated to be increasing by 40 GB daily The volume of ETM+ data is estimated to be increasing by 260 GB daily MSS = Multispectral Scanner System TM = Thematic Mapper ETM+ = Enhanced Thematic Mapper Plus			

3.6.1 Acquisition of Landsat satellite image from Landsat archive

The Landsat image data is a free online resource that any researcher can access. The whole dataset that could be accessed covers approximately 40 years beginning from the earth observation data produced since 1972 (Wulder *et al.,* 2008). In the early period of Landsat data, three main drivers were used as a means of accessing the data; first is proper right by data suppliers, the second is a licence requirement for working with data, and lastly prices at various levels for cost recovery (Wulder *et al.,* 2008). In early 2008 the US government, through the US Geological Survey (USGS), created an avenue for a 'free of charge' policy of accessing Landsat images, although for non-commercial usage. However one still needs to complete a formal registration with USGS before the data can be accessed. This is considered a huge bonus in monitoring global climate and environmental changes. From the archives of the Landsat images dated back to 1972, we have Landsat-1 images from where investigation into both natural and anthropic land use changes is possible. The effect of climate change becomes more apparent from 1972 when the world population almost doubled in its growth (Belward *et al.,* 2008; Woodcock *et al.,* 2008). Three different types of Landsat images were accessed from the archive based on the sensor that acquires each of the images; these were Landsat-4, Landsat-5 and Landsat-7. Although Landsat-8 is available in the archive, the algorithm for its processing is entirely different from the other Landsat. Hence, for the sake of continuity, Landsat-8 was not used in this study.

In investigating the land use changes in an environment, image data plays a crucial role; this is what Landsat data is used for in the research. Access to the Landsat database of satellite images was granted after the registration with the USGS website. The data is archived in rows and paths, Table 3.4. Ascertaining which row and path the location of study belongs to can be resolved with the use of the coordinates of a location in the study area. The major uncertainty and challenge of the dataset was cloud cover, which was a significant challenge to the remote sensing method using satellite images, especially in this tropical region. For this study, several Landsat images that were available in the archive had cloud cover. A selection of Landsat data has been made simple by the assemblage method done by the USGS and NASA to the global datasets (Townshend *et al.,* 2012). The collection of available Landsat data for this study was based on criteria including acquisition date, avoidance of cloud cover, gap-fill coverage, time of year, sensor choice and geographic uniformity. As Table 3.4 shows, the selected scenes which have somewhat different dates of collection, were chosen close to a time of year when it is believed that relative humidity will be at its lowest, hence a very clear cloud condition (Gutman *et al.,* 2008).

3.6.1.1 Scene selection

Image selection is difficult in the tropical regions where there is cloud cover almost all the year through. Only few images of the dry season period are reliable, these are Landsat scenes with less than 30 percent cloud cover.

Table 3.4: List of Landsat scenes with their reference number

Date	Reference Number	Path	Row	Sensor
24/12/1986	LM51910551986358AAA03	191	55	MSS
27/12/1990	LT41910551990361XXX03	191	55	TM
11/02/1999	LT51910551999042AAA03	191	55	TM
28/12/2002	LE71910552002362EDC00	191	55	ETM
07/12/2006	L71191055_05520061207	191	55	ETM+
11/01/2014	LE71910552014011ASN00	191	55	ETM
14/01/2015	LE71910552015014ASN00	191	55	ETM
01/01/2016	LE71910552016001ASN00	191	55	ETM

The various Landsat data shown in Table 3.4 were downloaded and archived. Figure 3.4 shows a detailed, step by step workflow in achieving the results of the study.

3.6.2 Landsat image processing

The Landsat satellites operated by USGS provide data free-of-charge with a spatial resolution of 30m per pixel for reflective bands; this is suitable for the full spectral monitoring studies from local to regional and global scale (Williams *et al.,* 2006). The USGS Landsat program is distinctive because of its universal image acquisition approach which allows land cover monitoring in any environment; this has been made possible over the last three decades. The reflective spectral bands (visible bands: band 1, band 2, band 3; near infrared band 4) provide abundant spectral profiles for vegetation type mapping and change detection in land cover. This is one of the reasons why Landsat imagery is suitable for any small change in land use of any environment. However, the Thermal Infrared (TIR) band (band 6) enables automatic detection of cloud cover; hence the Thermal Infrared Sensor (TIRS) measures land surface temperature in two thermal bands (band 6-1 and band 6-2). From the two different processed formats of the thermal band, band 6-2 was used in this research because it is of higher radiometric and geometric calibration, hence a small change can be easily detected. Landsat image spectral bands have the advantage of radiometric consistency and continuity between sensors used by the Landsat program, hence inter-calibration between the sensors is allowed.

Figure 3.4 summarizes the algorithm of the process routines that the acquired Landsat images were subjected to in order to acquire the change detection in and around the study area (Lagos Lagoon). Yet, it is argued by some investigations (Guha & Kumar, 2014; Lu *et al.,* 2011; Parece & Campbell, 2013) that thermal band 6 is not readily associated with surface type identification in the reflective part of the image spectrum because it could lead to misinterpretation of classification type. But in the algorithm for the processing of the Landsat images in this research, thermal band 6 had been included in the routine because of Land Surface Temperature (LST) which is expected as one of the outcomes of the process.

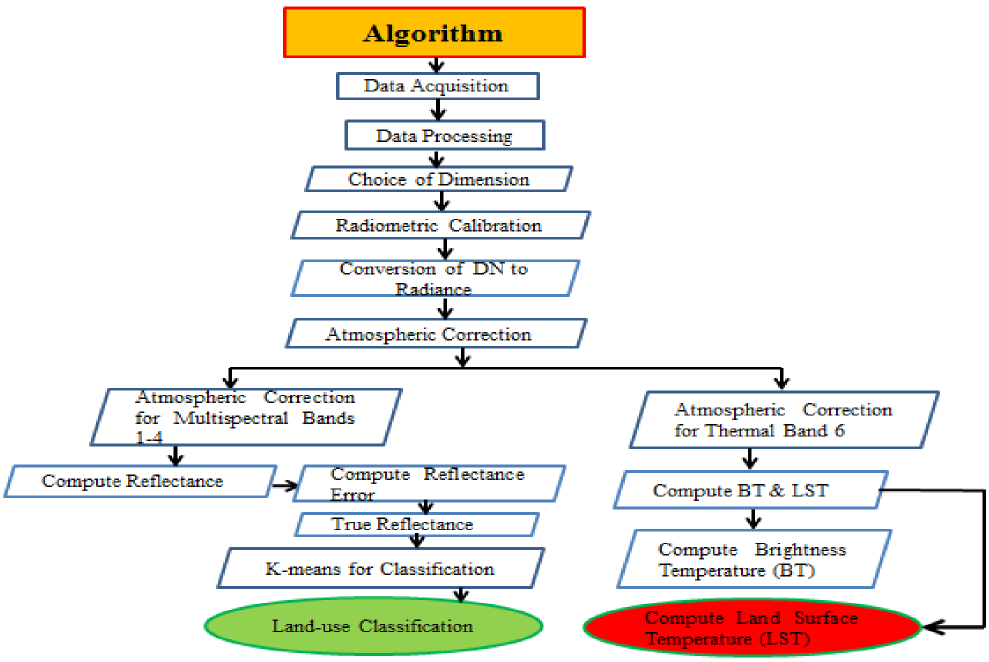


Figure 3.4: Algorithm diagram of methods of processing satellite image (Author)

Basically, eight procedures were involved in the algorithm which are:

3.6.2.1 Data acquisition

This is very paramount to the final results and the various inferences that will be concluded from this study. The quality of the data acquired is a function of the quality of the final results and conclusion that is finally generated from the study, hence that data acquisition has been discussed extensively under section 3.6.1.

3.6.2.2 Data Processing

The processing involved the following routines:

Choice of dimension – The geographic coverage of the Lagoon and its ecosystem which was covered in the research was marked out in the Google Earth map. The four corner coordinates of the coverage were recorded and this was fed into the window where the Landsat image was acquired to generate the image data of the actual area of study. This step was repeated for all the image scenes that were used in this study in order to determine the dimension required for the image to be downloaded.

Radiometric calibration - The pixel value recorded at an image point is the average reflected brightness from a specific region on the Earth (Chanda & Majumder, 2009). Always, there exists an atmospheric medium by which the reflected beam travels and the resultant distortion in the pixel value is termed as radiometric distortion. A basic understanding of radiometric knowledge of the image sensors is an important factor for the continuation of quantitative data from Landsat imageries (Thome, 2001). Among all the existing image data, the Landsat series of satellite imageries provided the longest continuous track of satellite-based data with a reliable high-spatial resolution (Chander *et al.*, 2009; Thome, 2001). As a result of this, Landsat is a very reliable and a vital means through which global changes in climate and environment can be monitored, hence a basic spatial medium used in decision making (Chander *et al.*, 2009; Masek et al., 2008;

Wulder *et al.*, 2008). The raw image data from Landsat are pixel numbers or Digital Numbers (DNs) with a range between 0 and 255. The values must be converted to units of absolute radiance values or physical units such as Top-Of-Atmosphere (ToA) reflectance before reflectance can be computed. This conversion can be done using a two-step process. The first step is to convert the DNs to radiance values using bias and gain values specific to the individual scene you are working with. The second step converts the radiance data to ToA reflectance.

Conversion of Digital Number (DN) to at-sensor spectral radiance - Radiance is the incident energy per solid angle leaving a unit surface area in a given direction. Radiance is measured at the sensor and is dependent on reflectance. The spectral radiance at the sensor's aperture (L_λ) is measured in watts/(m^2* ster * μm). This is a fundamental step in converting image data from multiple sensors and platforms to a physical unit which is a meaningful common radiance scale. The radiometric calibration of the Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Advanced Land Imager (ALI) sensors require rescaling of raw data numbers (Q) from the sensor transmitted from the satellite to calibrated digital numbers (Q_{cal}). Q_{cal} have the same radiometric scaling for all scenes on the ground for a specific period. During radiometric calibration, the raw unprocessed pixel value of image data are converted to physical units of absolute spectral radiance values using 32-bit floating-point calculation. The outputs of the absolute values are scaled to different bits depending on the type of sensor as shown in Table 3.5.

Table 3.5: Absolute maximum radiance value for different sensors

Sensor	Scaled binary digit	Radiance value (Q_{calmax})
MSS	7-bit	127
TM and ETM+	8-bit	255
ALI	16-bit	32767

The following equation is applied for the conversion for at-sensor spectral radiance L_λ

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{calmax} - Q_{calmin}}\right)(Q_{cal} - Q_{calmin}) + LMIN_\lambda \qquad \text{Equation 3.1}$$

or

$$L_\lambda = G_{rescale} \times Q_{cal} + B_{rescale} \qquad \text{Equation 3.2}$$

Where:

$$G_{rescale} = \frac{LMAX_\lambda - LMIN_\lambda}{Q_{calmax} - Q_{calmin}} \qquad \text{Equation 3.3}$$

$$B_{rescale} = LMIN_\lambda - \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{calmax} - Q_{calmin}}\right)Q_{calmin} \qquad \text{Equation 3.4}$$

Where

L_λ= Spectral radiance at the sensor's aperture [W/(m^2 ster μm)]

Q_{cal} = Quantized calibrated pixel value [DN]

Q_{calmin} = Minimum quantized calibrated pixel value corresponding to LMINλ [DN]

Q_{calmax} = Maximum quantized calibrated pixel value corresponding to LMAXλ [DN]

$LMIN_\lambda$= Spectral at-sensor radiance that is scaled to Q_{calmin} [W/(m^2 ster μm)]

$LMAX_\lambda$= Spectral at-sensor radiance that is scaled to Q_{calmax} [W/(m^2 ster μm)]

Grescale = Band-specific rescaling gain factor [(W/(m^2 ster μm))/DN]

Brescale = Band-specific rescaling bias factor [W/(m^2 ster μm)]

Originally, the calibration information units for MSS and TM sensor was mW/(cm^2 ster μm)], but for the purpose of consistency with ETM+ spectral radiance, the units of W/(m^2 ster μm)] was maintained for both MSS and TM calibration information.

The above equation was program in Matlab in order to compute resolute radiance values for the various Landsat scenes that were used in the study.

Atmospheric correction - The presence of water vapour and other gases in the atmosphere (oxygen, nitrogen, argon, carbon dioxide, hydrogen, ozone methane, neon, helium, krypton) cause absorption, reflection and refraction effects on electromagnetic rays coming to the satellite. For this reason there is a need to correct for the refraction, reflection and absorption caused on the electromagnetic rays coming to the satellite and passing through the atmosphere before reaching the object of study on the Earth. The correction in this section is two-fold, thermal correction for band 6 and atmospheric correction for multispectral bands 1-4.

Atmospheric correction for thermal band 6 - Reducing to the barest minimum the atmospheric effects at the thermal region is very important for the use of thermal band imagery for temperature studies (Barsi *et al*., 2005). Typically, the computation of atmospheric transmission is difficult and time consuming. In order to accomplish this task, the user has to source out the atmospheric data, convert it to a format that was compatible to the radiative transfer model and blend the results over the proper band pass. This process takes a long time to accomplish, but the automatic Atmospheric Correction Parameter Calculator (ACPC) eases this computation. The calculator is available at http://atmcorr.gsfc.nasa.gov. This web-based calculator requires the specific acquisition date, time of the image and location, as shown in Figure 3.5. The outputs from this calculator are parameters used for converting the satellite radiance to surface radiance.

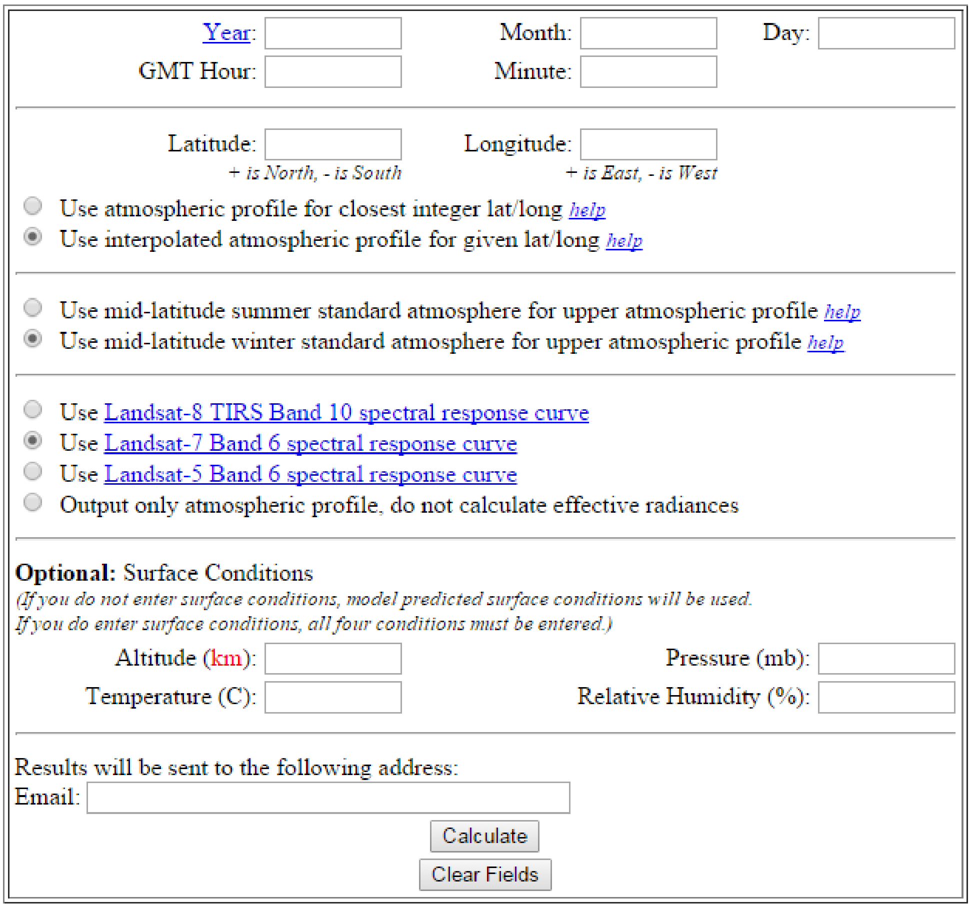


Figure 3.5: The Web-based Atmospheric Correction Parameter Calculator (Barsi *et al.*, 2005)

The modelled atmospheric profile interpolation enhances the user to have three different options from the calculator to select band pass (TM band pass, ETM+ band pass, or no spectral band pass).

The calculated results are mailed to the user and output to the window calculator on the web browser. The output file (Figure 3.5) consists of not only the integrated transmission, upwelling and downwelling radiances for the study site, but it also contains the atmospheric data used to generate the result. When no spectral band pass is selected on the calculator, the result generated is the interpolated atmospheric profiles; this is used in the radiative transfer model.

Although the calculator generates parameters for a single point, it is also appropriate for use in areas where there is no significant change in elevation. Since the Lagoon coastal plain is low lying with no significant change in elevation, this calculator is adequate to describe the atmosphere across the Landsat scene of the entire Lagoon ecosystem.

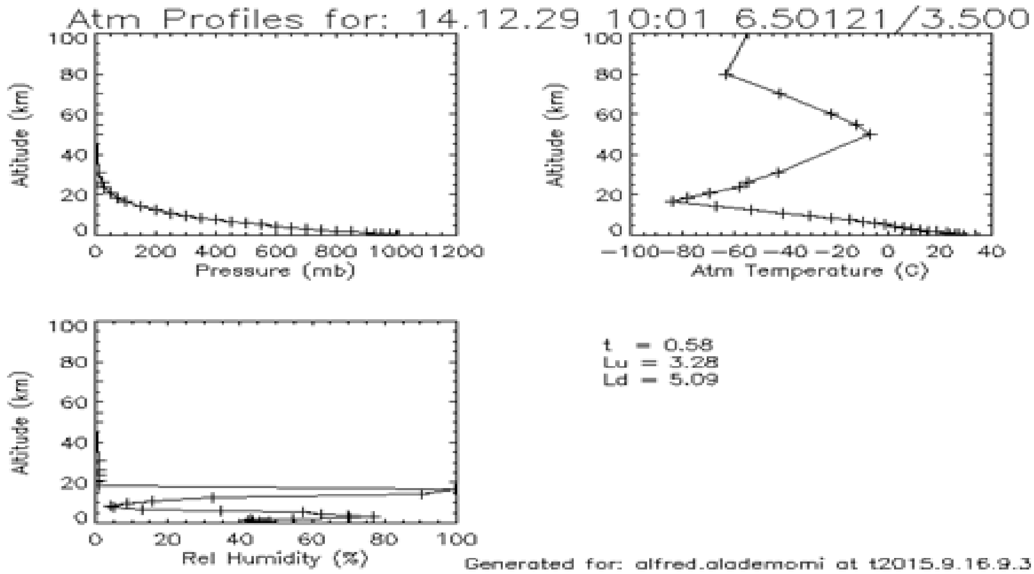


Figure 3.6: Integrated atmospheric profile plot generated from the Atmospheric Correction Parameter Calculator

Atmospheric correction for multispectral bands 1-4 - Dense vegetation pixels can be identified in Landsat imagery under a wavelength of around 2.1 µm (Liang *et al.,* 2001). Their reflectance has strong correlations with band 1 (Blue) and band 2 (Green) reflectance, a very low reflectance in the visible or multispectral spectrum, hence they are referred to as “dark objects.” The method is probably the most popular atmospheric correction method and has been for a long time (Kaufman *et al.,* 2000; Liang *et al.,* 2001). The approach for this correction is to choose the darkest small portion in the Landsat scene to be investigated, record the coordinates of the small portion and then use it for the computation of reflectance of the small location. This is later used for reflectance correction in the latter part of the algorithm.

Conversion from Radiance to Reflectance - To minimise scene-to-scene variability, the at-sensor spectral radiance must be converted to ToA reflectance. In comparing images from different sensors, three main advantages are embedded in the use of ToA. Firstly, it removes the cosine effect of different sun angle elevations due to the time difference between data acquisitions. Secondly, it compensates for the different values of solar irradiance coming from spectral band differences. Thirdly, it corrects for the Earth-Sun distance between different data acquisition dates, this difference can be geographically and temporarily significant. This method was developed by (Chavez, 1996), and the basic merit of the method is that the data needed to carry out the atmospheric correction are obtained from the image scene itself. The at-surface reflectivity is calculated with the equation:

$$Rt_i = \frac{\pi \times L_\lambda \times d^2}{(Eo_i \times T_o \times T_1) \times \mathrm{Cos}\,(\theta_z)} \qquad \text{Equation 3.5}$$

Where

Rt_i = ToA planetary reflectance

Π = 3.412

L_λ = spectral radiance at sensor's aperture

d = Earth-Sun distance in astronomical units

$(Eo_i \times T_o \times T_1)$ = Mean solar irradiance

θ_z = Solar zenith angle = 90 – Sun elevation (θ_{SE}).

Note that the cosine of the solar zenith angle is equivalent to the sine of the solar elevation angle. The d values are obtained from Nautical Almanac Office; this was published online via the sun distance table (Table 3.6) on landsathandbook.gsfc.nasa.gov/excel_docs/d.xlsTable (NASA, 2011).

Table 3.6: Earth-Sun distance table

Earth-Sun distance (d) in astronomical units for Day of the Year (DOY)											
DOY	D	DOY	d	DOY	D	DOY	d	DOY	D	DOY	D
1	0.983	61	0.991	121	1.007	181	1.016	241	1.009	301	0.993
2	0.983	62	0.991	122	1.007	182	1.016	242	1.009	302	0.993
3	0.983	63	0.991	123	1.008	183	1.016	243	1.009	303	0.993
4	0.983	64	0.991	124	1.008	184	1.016	244	1.009	304	0.992
5	0.983	65	0.992	125	1.008	185	1.016	245	1.009	305	0.992
6	0.983	66	0.992	126	1.008	186	1.016	246	1.008	306	0.992
7	0.983	67	0.992	127	1.009	187	1.016	247	1.008	307	0.992
8	0.983	68	0.992	128	1.009	188	1.016	248	1.008	308	0.991
9	0983	69	0.993	129	1.009	189	1.016	249	1.008	309	0.991
10	0.983	70	0.993	130	1.009	190	1.016	250	1.007	310	0.991
11	0.983	71	0.993	131	1.010	191	1.016	251	1.007	311	0.991
12	0.983	72	0.993	132	1.010	192	1.016	252	1.007	312	0.990
13	0.983	73	0.994	133	1.010	193	1.016	253	1.007	313	0.990
14	0.983	74	0.994	134	1.010	194	1.016	254	1.006	314	0.990
15	0.983	75	0.994	135	1.010	195	1.016	255	1.006	315	0.990
16	0.983	76	0.995	136	1.011	196	1.016	256	1.006	316	0.989
17	0.983	77	0.995	137	1.011	197	1.016	257	1.005	317	0.989
18	0.983	78	0.995	138	1.011	198	1.016	258	1.005	318	0.989
19	0.983	79	0.995	139	1.011	199	1.016	259	1.005	319	0.989
20	0.984	80	0.996	140	1.011	200	1.016	260	1.005	320	0.988
21	0.984	81	0.996	141	1.012	201	1.016	261	1.004	321	0.988
22	0.984	82	0.996	142	1.012	202	1.016	262	1.004	322	0.988
23	0.984	83	0.997	143	1.012	203	1.016	263	1.004	323	0.988
24	0.984	84	0.997	144	1.012	204	1.015	264	1.004	324	0.988
25	0.984	85	0.997	145	1.012	205	1.015	265	1.003	325	0.987
26	0.984	86	0.997	146	1.013	206	1.015	266	1.003	326	0.987
27	0.984	87	0.998	147	1.013	207	1.015	267	1.003	327	0.987
28	0.984	88	0.998	148	1.013	208	1.015	268	1.002	328	0.987
29	0.985	89	0.998	149	1.013	209	1.015	269	1.002	329	0.987
30	0.985	90	0.999	150	1.013	210	1.015	270	1.002	330	0.986
31	0.985	91	0.999	151	1.013	211	1.015	271	1.002	331	0.986
32	0.985	92	0.999	152	1.014	212	1.015	272	1.001	332	0.986
33	0.985	93	0.999	153	1.014	213	1.015	273	1.001	333	0.986
34	0.985	94	1.000	154	1.014	214	1.014	274	1.001	334	0.986
35	0.985	95	1.000	155	1.014	215	1.014	275	1.000	335	0.986
36	0.986	96	1.000	156	1.014	216	1.014	276	1.000	336	0.985
37	0.986	97	1.001	157	1.014	217	1.014	277	1.000	337	0.985
38	0.986	98	1.001	158	1.014	218	1.014	278	1.000	338	0.985
39	0.986	99	1.001	159	1.015	219	1.014	279	0.999	339	0.985
40	0.986	100	1.001	160	1.015	220	1.014	280	0.999	340	0.985
41	0.986	101	1.002	161	1.015	221	1.013	281	0.999	341	0.985
42	0.987	102	1.002	162	1.015	222	1.013	282	0.998	342	0.985
43	0.987	103	1.002	163	1.015	223	1.013	283	0.998	343	0.984
44	0.987	104	1.003	164	1.015	224	1.013	284	0.998	344	0.984
45	0.987	105	1.003	165	1.015	225	1.013	285	0.998	345	0.984
46	0.987	106	1.003	166	1.015	226	1.013	286	0.997	346	0.984
47	0.987	107	1.003	167	1.015	227	1.012	287	0.997	347	0.984
48	0.988	108	1.004	168	1.015	228	1.012	288	0.997	348	0.984
49	0.988	109	1.004	169	1.016	229	1.012	289	0.996	349	0.984
50	0.988	110	1.004	170	1.016	230	1.012	290	0.996	350	0.984
51	0.988	111	1.004	171	1.016	231	1.012	291	0.996	351	0.984
52	0.989	112	1.005	172	1.016	232	1.011	292	0.996	352	0.984
53	0.989	113	1.005	173	1.016	233	1.011	293	0.995	353	0.983

DOY	D	DOY	d	DOY	D	DOY	d	DOY	D	DOY	D
54	0.989	114	1.005	174	1.016	234	1.011	294	0.995	354	0.983
55	0.989	115	1.006	175	1.016	235	1.011	295	0.995	355	0.983
56	0.989	116	1.006	176	1.016	236	1.011	296	0.994	356	0.983
57	0.990	117	1.006	177	1.016	237	1.010	297	0.994	357	0.983
58	0.990	118	1.006	178	1.016	238	1.010	298	0.994	358	0.983
59	0.990	119	1.007	179	1.016	239	1.010	299	0.994	359	0.983
60	0.990	120	1.007	180	1.016	240	1.010	300	0.993	360	0.983
361	0.983	362	0.983	363	0.983	364	0.983	365	0.983	366	0.98

Applying reflectance error - The coordinates of the darkest small portion of the image discussed under atmospheric correction for multispectral bands 1-4 are used in Equation 3.5 to compute reflectance for the small portion, this stands as an error to be applied to the reflectance computed for the whole Landsat scene, hence the true reflectance is computed as:

$R = Rt_i - \text{error}$ Equation 3.6

R = True reflectance

Rt_i = Computed reflectance

Error = reflectance computed for darkest point

Computation of Brightness Temperature (BT) from spectral radiance - The next step is to convert the spectral radiance to at-sensor brightness temperature which is referred to as black body temperature. The at-sensor brightness temperature assumes that the Earth's surface is a black body including atmospheric effects. In this computation, the values generated from the atmospheric calculator as *t*, L_u and L_d (transmittance, upwelling radiance and downwelling radiance respectively) are used in Equation 3.7 to compute brightness temperature (BT).

$$BT = \frac{(LB6 - stn_i\,uwr)}{(emissivity \times stn_i tr)} - \left((1 - emissivity)/(emissivity \times stn_i dwr)\right)$$ Equation 3.7

Where

BT = Brightness Temperature

LB = Radiance

$stn_i\ uwr$ = upwelling radiance

$stn_i dwr$ = station downwelling radiance

$stn_i tr$ = station transmittance

Emissivity is derived from the Look up Table

Emissivity - The understanding of land surface emissivity (LSE) is very important in order to successfully apply Equation 3.7 to a Landsat image (Sobrino *et al.*, 2004). Emissivity is the ability of an object to emit infrared energy, hence infrared emissivity is a property commonly used to identify planetary compositions of atmospheres and surfaces (Ramsey & Gillespie, 2012). A blackbody material has approximate emissivity close to 1; in this case the emitted radiance follows a Planck distribution and is the maximum possible value for a given temperature (Ramsey & Gillespie, 2012). In order to compute the emissivity value used in Equation 3.7, emissivity values for the four major classifications of the Lagoon ecosystem (water, built-up area, bare soil and vegetation) were obtained from a Look Up table (LUT) from different authors (Snyder *et al.,* 1998). The emissivity value as recorded by various authors has both maximum and minimum values; in this study, averages of minimum and maximum values of the emissivity were taken for the four classifications used. The Landsat scene for the study area was assumed to occupy landed area of 100%, hence each of the classification types was allocated the percentage proportion of the area they occupied from the entire study area. Emissivity was computed for each of the classifications based on the percentage area occupied from the study location; this was summed together to obtain the emissivity for the area.

Computation of Land Surface Temperature (LST) - Thermal band (band 6) of Landsat data was also converted from spectral radiance to LST. The computation was done using the prelaunch calibration constants in Table 3.7. The conversion formula from at-sensor spectral radiance to Land Surface Temperature uses the Planck formula (Barsi *et al.*, 2005):

$$LST = \frac{K2}{\ln\left(\frac{K1}{L_\lambda}+1\right)} \qquad \text{Equation 3.8}$$

Where

LST = Effective at-sensor temperature (Kelvin)

K1 = pre-calibration constants 1 (W/ (m^2 ster µm))

K2 = pre-calibration constant 2 (Kelvin)

$L\lambda$ = spectral radiance (W/(m^2 ster µm))

Table 3.7: Calibration constants for TM and ETM+ thermal band

Sensor	**Constant K1 (W/(m^2 ster µm))**	**Constant K2 (Kelvin)**
L4 TM	671.62	1284.30
L5 TM	607.76	1260.56
L7 ETM+	666.09	1282.71

Land cover classification type - Finally, immediately after the reflectance error was computed, the corrected reflectance is calculated thereafter – a k-means cluster tool was used from Matlab R2013a software to the corrected reflectance to obtain the four land use classification types.

3.6.3 Lagos Lagoon wetlands' spatial variability

Due to cloud problems Landsat images that were used for this section just like section 3.6.2 were collected between the month of December and January. Three scenes of Landsat TM (Thematic Mapper) of 1984, Landsat TM of 2002 and Landsat 8 of 2015 were processed to extract the swamps, mangroves, built up area, vegetation and water bodies across the area of study. In order to identify the five classification features very distinctly, bands 3, 4 and 5 were used for a colour composite. This process made it possible to see clear changes that have taken place in the Lagoon over that period of time (31 years).

In this section the image classification method used was a supervised classification. This was chosen because of the ease with which it identifies the wetlands distinctly and it also simplifies the editing stage. Using ENVI (Environment for Visualising Images) software, a parallelepiped supervised classification which uses a simple decision rule to classify multispectral data (Richards & Richards, 1999) was used on the trained classes and then used to extract the wetlands from the multispectral images of the three distinct dates, independently.

The output of the classification showed swamps, mangroves, built-up areas, vegetation, water bodies and a few other features picked as a result of similar spectral reflectance. A post classification exercise, auto vectorisation, of the output was executed; the vectorised classification results were then exported to ArcMap as shapefiles for editing, change detection and calculation of areas. Analysis was done on the final results, inferences were made and final conclusions drawn.

3.6.4 Current meter data

In order to study and analyse hydrodynamic changes in the Lagoon, the key data requirements of salinity, depth, conductivity, speed, direction and density were collected from the Lagoon. A Valeport current meter, model 106 (Figure 3.8) was employed for the collection of this data in the Lagos Lagoon. The instrument was simple to use with either the Windows based PC software supplied or with an optional dedicated Control Display Unit (CDU). The Valeport current meter has five sensors that measure, speed, direction, temperature, conductivity and pressure. However, the following parameters, salinity, speed of sound and density were derived from the conductivity, temperature and pressure readings using Chen and Millero formulae (Alkan *et al.,* 2006). The data acquisition mode for the equipment is based on a 5 second period vector average during which impeller counts are measured and a single compass reading is made. The vector average is built up over the averaging period set (average period is any multiple of 5 seconds, up to a maximum of 30 minutes). The real time data display is updated at the end of each averaging period. Figure 3.7 shows the sample locations where in-situ data (hydrodynamic and sediment samples) were collected on the Lagoon, the map also depicts the extent that the author's data covered on the Lagoon. However, Table 3.8 shows the combined variable data extracted from the in-situ data, demographic and Landsat images which represent the overview of the data used in the research.

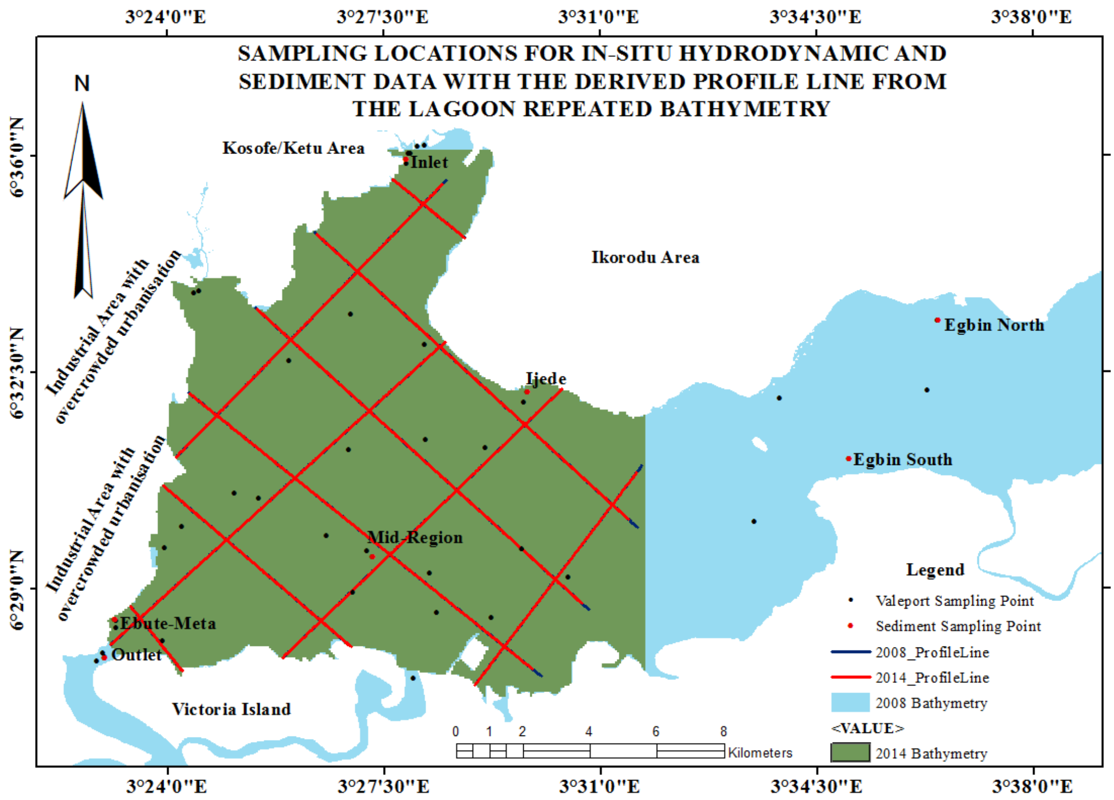


Figure 3.7: Map showing sampling locations on the Lagoon. Points in red are locations where sediments and water samples were collected while the points in black are locations where in-situ hydrodynamic data were collected

Table 3.8: Overview of extracted data variables that was used in the research

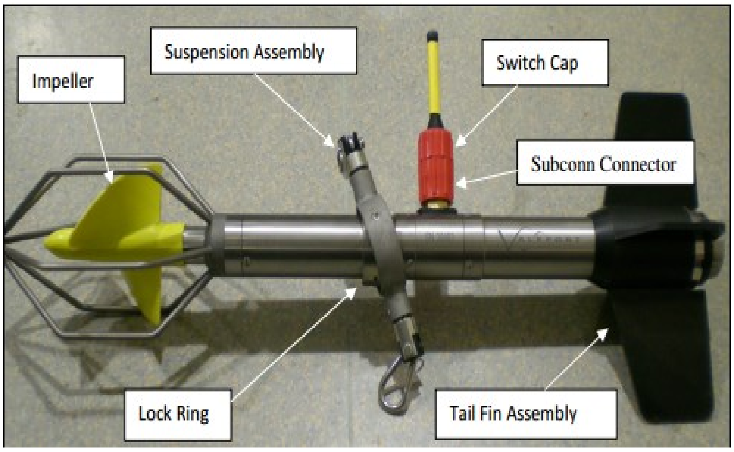
Data Type	Variable Extracted	Coverage
In-situ Hydrodynamic data	Salinity, Speed, Temperature, Density, Depth, Pressure, Direction, Speed of Sound	Approximately half of the Lagoon water
In-situ sediment sample	Water sample and Sediment sample	Seven locations within the lagoon
Landsat image	LST	The LGA that surround the Lagoon with its ecosystem
Landsat image	NDVI	The LGA that surround the Lagoon with its ecosystem
Landsat image	Coverage area for Mangrove, built-up, swamp, vegetation, and bare-land,	The LGA that surround the Lagoon with its ecosystem
Demographic data	Population of Lagos State	Covers the investigated LGA within the Lagoon ecosystem

Two different data collection campaigns were launched in order to gather a complete seasonal data (wet and dry season). The data collection for the dry season was acquired in April 2014 while the wet season data was collected in October to early December 2014 when there was heavy rainfall in the region. With the Valeport current meter there is software that downloads the data from the equipment's Control Display Unit (CDU) and converts the data to Excel format which is easy to interpret and interact with. Table 3.9 shows a data sample from the Valeport Current meter.

Table 3.9: Sample of downloaded data from Valeport current meter

DOS file : 0_CDU_0108_033724.000
Instrument file No : 0
Sample period : 5 seconds
Average period : 1 samples, 5 seconds
Parameters installed : Speed, Direction, Pressure, Temperature And Conductivity
Calibrated ascii data

Date/Time	Speed (m/s)	Direction (deg)	Pressure (dBar)	Temp (°C)	Cond. (mS/cm)	Salinity (PSU)	Density Anomaly (kg/m^3)	Speed of Sound (m/s)
09/04/2014 12:09	0.359	275.84	1.003	31.41	6.078	2.89	-2.629	1515.438
09/04/2014 12:09	0.359	275.23	0.998	31.44	6.069	2.884	-2.641	1515.482
09/04/2014 12:09	0.417	278.45	0.977	31.45	6.005	2.851	-2.669	1515.471
09/04/2014 12:10	0.359	279.59	1.003	31.45	5.84	2.767	-2.732	1515.388
09/04/2014 12:10	0.417	280.2	0.998	31.43	5.561	2.628	-2.83	1515.201
09/04/2014 12:10	0.417	279.59	1.024	31.41	5.523	2.61	-2.838	1515.143
09/04/2014 12:10	0.417	273.38	1.035	31.43	5.773	2.735	-2.748	1515.304
09/04/2014 12:10	0.417	273.99	0.988	31.41	6.568	3.139	-2.444	1515.698
09/04/2014 12:10	0.474	280.2	0.967	31.38	5.884	2.793	-2.691	1515.268
09/04/2014 12:10	0.474	274	0.977	31.34	6.101	2.906	-2.593	1515.286
09/04/2014 12:10	0.474	273.38	0.993	31.30	5.723	2.717	-2.721	1515.001
09/04/2014 12:10	0.244	288.97	1.024	31.27	5.324	2.517	-2.86	1514.72
09/04/2014 12:10	0.13	276.46	1.076	31.26	4.995	2.352	-2.981	1514.54
09/04/2014 12:10	0.187	288.99	1.196	31.27	6.063	2.891	-2.581	1515.117



(i)

(ii)

Figure 3.8: Valeport Current Meter (i) Segment that is deployed into water (ii) CDU segment that stored collected data

The first set of data, for the dry season data, was subjected to statistical analysis to test the correlation of the different data before embarking on their use. Data parameters of high correlation were good for building a strong model. Figure 3.9 shows the results of the test where a matrix plot of the current meter data shows the various relationships that existed between the collected data. From the figure it was deduced that conductivity, salinity and density have a strong correlation, hence they can be used to build a strong model that speaks clearly about any change that occurs in the Lagoon water body. The fact that there was no strong correlation between the other data does not mean they are not appropriate for use, they were used for other computation and analysis.

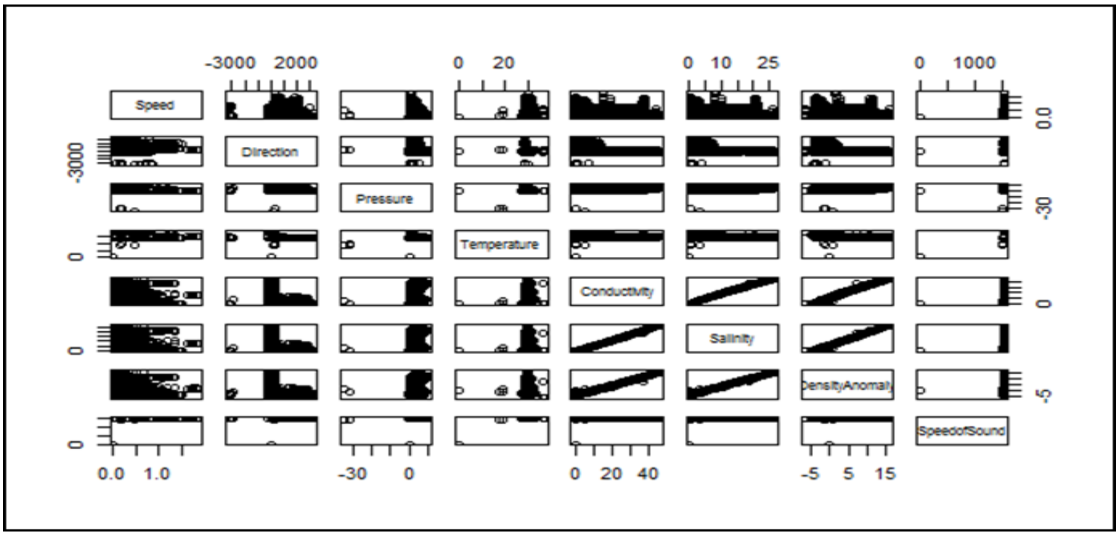


Figure 3.9: Matrix plot of current meter data showing their relationship

3.7 Development of models for investigating sediment accretion and effect of sea level variation

The net rate of change in the elevation of marsh surface $\left(\frac{d_z}{d_t}\right)$ in any lagoon could be understood to be equivalent to the net rate of accretion (mineral and organic matter accumulation minus subsidence) and is proportional to the depth (D) of the marsh surface below mean high tide.

That is $\frac{d_z}{d_t}\ \alpha\ D^n$ Equation 3.9

The rate of change of elevation of the marsh platform is also the positive function of the standing density of plant biomass, or above ground production (B)

$\frac{d_z}{d_t}\ \alpha\ (q + KB)^m$ Equation 3.10

Combining Equation 3.9 and 3.10, the change in elevation of the marsh surface within the plant's growth range is written as:

$\frac{d_z}{d_t} = \beta(q + KB)^m \times D^n$ For D > 0 Equation 3.11

Where β, m and n are constants of proportionality to be determined, based on whether the rate of sea level change is linear or exponential.

Equation 3.11 can be accounted for as representing a family of equations with different coefficient values that apply to different zones, within and around the lagoon landscape, depending on the number of rivers that feed into the system and underground drainage flow into the lagoon.

The variable B in Equation 3.11 is a function of D. This is dependent on the productivity of marsh elevation (B) relative to mean sea level, according to (Morris *et al*., 2002) this could be approximated and represented as:

$B = aD + a\mathrm{b} + \mathrm{c}$ Equation 3.12

Where a, b and c are coefficients that determine the depth limits and magnitude of B

So, the rate of change can be mathematically represented as:

$\frac{d_z}{d_t} = \beta[q + \mathrm{k}(aD + bD^2 + c)]^m D^n$ Equation 3.13

Equilibrium and non-equilibrium conditions can be considered around the Lagoon location relative to sea level rise.

3.7.1 Equilibrium condition

β is introduced for dimensional homogeneity with Morris *et al.* 2002. For a marsh in equilibrium with mean sea level, the rate of change of marsh elevation $\left(\frac{d_z}{d_t}\right)$ is equal to the long-term rate of change in sea level$\left(\frac{d_Y}{d_t}\right)$, that is

$\frac{d_Z}{d_t} = \frac{d_Y}{d_t}$ (Equilibrium condition) Equation 3.14

Case I

Assuming that the long-term sea level is rising at constant rate R, the equation 3.14 can be represented as:

$\frac{d_Y}{d_t} = R$, that is $\frac{d_Z}{d_t} = \frac{d_Y}{d_t} = R$ Equation 3.15

Equation 3.13 implies that

$\beta[q + k(aD + bD^2 + c)]^m D^n = R$ Equation 3.16

To recover the Morris equation, we assume that β is a constant of proportionality; m and n as exponential proportionality are equal and have value of 1 that is:

B = m = n = 1,

That is $qD + kaD^2 + kbD^3 \, kCD = R$ Equation 3.17

$kbD^3 + kaD^2 + (q + KC)D - R = 0$ Equation 3.18

Solving Equation 3.18, it becomes

$D^3 + \left(\frac{a}{b}\right) D^2 + \left(\frac{q+KC}{Kb}\right) D - \frac{R}{Kb} = 0$ Equation 3.19

Let $D = x - \frac{a}{3b}$ Equation 3.20

Substituting Equation 3.20 into Equation 3.19, we have

$[x - \frac{a}{3b}]^3 + \frac{a}{b}\,[x - \frac{a}{3b}]^2 + \left(\frac{q+kC}{Kb}\right)\left(x - \frac{a}{3b}\right) - \frac{R}{kb} = 0$ Equation 3.21

Solving Equation 3.21, it becomes

$x^3 + \frac{1}{b}\left(\frac{q+kC}{k} - \frac{a^2}{3b}\right) + \frac{1}{b}\left[\frac{8a^3}{27b^2} - \frac{a(q+kC)}{3kb} - \frac{R}{k}\right] = 0$ Equation 3.22

Therefore, Equation 3.22 can be written as:

$x^3 + \lambda_1 x + \lambda_2(R) = 0$ Equation 3.23

Where $\lambda_1 = \frac{1}{b}\left(\frac{q+kC}{k}\right) - \frac{a^2}{3b}$

$$\lambda_2 = \frac{1}{b}\left[\frac{8a^2}{27b^2} - \frac{a(q+kC)}{3kb} - \frac{R}{k}\right]$$

Using Cardan's method, three roots x_1, x_2, x_3 are obtained. Solution to the root equations can be achieved using D'Moivre's theorem.

Recall that $D = x - \frac{a}{3b}$, hence:

$$\left.\begin{aligned} D_1 &= x_1 - \frac{a}{3b} \\ D_2 &= x_2 - \frac{a}{3b} \\ D_3 &= x_3 - \frac{a}{3b} \end{aligned}\right\} \qquad \text{Equation 3.24}$$

Equation 3.24 is the roots of equation 3.18. These roots are part of the solution to equation 3.18 which was used to form a model for rate of change of marsh elevation when it was assumed to be in equilibrium with mean sea level.

Case II

Assuming that the long-term sea level is rising at linear rate

$$r_0 + \alpha t = R \qquad \text{Equation 3.25}$$

Therefore $\frac{dY_1}{dt} = R_0 + \propto t = R_{(t)}$ Equation 3.26

For the equation condition,

$$\frac{dZ}{dt} = \frac{dY_1}{dt} = r_0 + \propto t \qquad \text{Equation 3.27}$$

Recall Equation 3.26 and replace R with $r_0 + \propto t$, hence the equation becomes

$$kbD^3 + kaD^2 + (q + KC)D - \frac{R(r_0,t)}{kb} = 0 \qquad \text{Equation 3.28}$$

Where $R = r_0 + \propto t$

Hence Equation 3.28 can be solved in a similar way to Equation 3.18

Case III

Another scenario that can be considered for modelling the marsh elevation in the Lagoon ecosystem is the case where the long-term sea level is assumed to be increasing at exponential rate, in this scenario, the rate of change could be written thus:

$$R_1 = r_0 e^{\propto t} \qquad \text{Equation 3.29}$$

Applying this to Equation 3.28, the equation becomes

$$kbD^3 + kaD^2 + \left(\frac{q+KC}{kb}\right)D - \frac{R_1(r_0,t)}{kb} = 0 \qquad \text{Equation 3.30}$$

Equation 3.30 can be solved the same way as Equation 3.18; the result gives rise to an exponential rate at a state of equilibrium.

The three cases (constant, linear and exponential rates of change) that were considered under equilibrium condition can be considered for a non-equilibrium state. If the marsh elevation of the lagoon is not in equilibrium with the mean sea level, it is expected that the rate of change of marsh elevation $\left(\frac{dZ}{dt}\right)$ is not equal but rather proportional to long-term rate of change in sea level $\left(\frac{dY}{dt}\right)$.

Hence, $\frac{dZ}{dY} \propto \frac{dY_1}{dZ}$ Equation 3.31

$$\frac{dZ}{dY} = \varphi \frac{dY_1}{dZ} \qquad \text{Equation 3.32}$$

Where φ equals the constant of proportionality for the non-equilibrium condition.

Case I

Assuming that the sea level is rising at constant rate r

Then $\frac{dZ}{dt} = \frac{dY_1}{\varphi dZ} = R$ Equation 3.33

Hence $kbD^3 + kaD^2 + \left(\frac{q+KC}{Kb}\right)D - \frac{R}{\varphi Kb} = 0$ Equation 3.34

Case II

Assuming that the sea level is rising at linear rate

$\frac{dZ}{dt} = \frac{dY_1}{\varphi dZ} = \frac{R_0 + \propto t}{\varphi kb} = 0$ Equation 3.35

Hence $kbD^3 + kaD^2 + \left(\frac{q+KC}{Kb}\right)D - \frac{R_0 + \propto t}{\varphi kb} = 0$ Equation 3.36

Case III

Assuming the rate of sea level rise is exponential

$\frac{dZ}{dt} = \frac{dY_1}{\varphi dZ} = \frac{R_0 e^{\propto t}}{\varphi kb} = 0$ Equation 3.37

$kbD^3 + kaD^2 + \left(\frac{q+KC}{Kb}\right)D - \frac{R_0 e^{\propto t}}{\varphi kb} = 0$ Equation 3.38

Equations 3.34, 3.36 and 3.38 could be solved in similar way to Equation 3.30

The models in this section were coded and executed in Matlab R2013a, results generated were discussed and analysed in one of the sections in chapter five or six respectively. The following were the Matlab toolboxes used in performing the Matlab programming:

- Matlab Compiler Runtime – for code compilation and for code deployment process

- File I/O Functions – used for file stream auto-import into Matlab, this was what was used to import the Excel spreadsheets containing the data into Matlab workspace. This was used to build the observation matrix in conjunction with vector manipulations. From here the Least Square equation is assembled.
- Finally plot tool was used for plotting of the various graphs involved with the help of graphic functions for annotate the graph

Unlike the execution of the models in this section which was mainly done with Matlab, the next section of modelling was done using software developed in an ArcGIS environment.

3.8 Modelling in ArcGIS

3.8.1 Salt intrusion model

This section deals with the development of a model to ascertain the assessment of salt intrusion on the Lagoon studied, based on four scenarios of prevailing tidal strength – low water (LW) band, high water (HW) band, mid-ebb band and mid-flood band. The model showcases the patterns of stratification in the Lagoon during different seasons at different tidal strengths. A summary of the steps and methods to achieve this are as follows:

Spatially disaggregated data (the numerical current meter data) was obtained in the Lagoon at spatial locations, this included salinity data of the Lagoon water.

The data was normalised using ArcGIS 10.1 in order to control the data input in a specific domain, this helped in the convergence of the data and ensured consistency and integrity constraints. ArcGIS is a platform used for accomplishing a database system in which the organising principle is explicitly spatial - Geographic Information System (GIS) is used in building, managing and connects geographic information using features and tabular data, imagery, maps and 3D data. It compiles and manages geographic data layers that power the GIS. The geodatabase components stores and manages features for the ArcGIS and enable spatial relationships and behaviour (such as networks and topologies) on geographic data. ArcGIS helps to fulfil the following five steps process that enables application of GIS to problems that require a geographic decision:

- What is the problem to be solved or analysed and where it is located, framing the question will help to decide what to analyse and how to present the results to the audience.
- Acquiring the required type of data and the geographic scope of the project, this helps to direct the method of data collection and conduction of analysis.
- Organise and manage the data in the format that make it easy for analysis.
- ArcGIS as GIS modelling tool help to perform geographic analysis, this toll makes it relatively easy to make changes and create new output.
- Lastly, ArcGIS makes it easy to tailor the results of any GIS project in a format that is preferable by different audience.

This GIS was employed to plot and normalise salinity values. The data plot was spatially represented on the Lagoon map that had already been uploaded to ArcGIS based on the four scenarios of prevailing tidal strength (HW, LW, mid-ebb and mid-flood). The data was also plotted based on the two prevailing seasons of the region where the study was carried out.

To ascertain the stratification of the Lagoon was properly modelled, salinity at the top and bottom layer of the Lagoon at different tidal strengths was plotted separately.

The spatial analysis tool in ArcGIS was applied with all its functions to model the Lagoon stratification profile. From Math tool, the Minus and Divide tools were employed for the data normalization with minimum and maximum values of the dataset used as constant values for the input raster.

Computed stratification values were also plotted separately and compared with the result obtained from the model.

3.8.2 Modelling Lagoon coastline changes

Intrinsic to this study was a qualitative analysis that enabled the examination of geographic patterns in the dataset, involving models that mimic the real world with the combination of several layers of data. The maps produced in the course of this research were the result of models developed within the GIS framework. GIS models were employed in this study as they help to automate geoprocessing workflow, share geoprocessing knowledge and record and document methodology. The study used the ArcGIS 10.1 ModelBuilder to develop the models for coastline changes. The model's structure used for this work consisted of the tools, project data and derived data. The tools were obtained from the Arctoolbox in ArcGIS, the input dataset was the project data, while geoprocessing from the ArcGIS ModelBuilder delivered the derived dataset.

This section is about communicating the Lagoon coastline changes; therefore it was important to share knowledge in preparation of the data for analysis and modelling the workflow. The method adopted in this study to communicate information and the eventual changes on the coastline follow the steps in Table 3.10.

Table 3.10: Basic GIS project adopted

Steps	Tasks
Determine the objectives of the project	Identify the problem to solve Break down the problem into measurable criteria Determine data requirements
Build the database and prepare the data for analysis	Identify and obtain relevant data Design and implement the database Add spatial and attribute data to the database Manage and modify the data
Perform the analysis	Determine methodology and sequence of operations Process the data Evaluate and interpret the results Refine the analysis as needed and generate alternatives
Present the results	Create final products for intended audience

Source: (Allen, 2011)

The objective in using ArcGIS was to string tools together, form a model workflow and to accomplish the task of quantifying the changes of level in the Lagoon coastline over time. The data involved was coastline data of the Lagoon, which was digitised from Landsat images. The various digitised coastline maps of the Lagoon were uploaded into ArcGIS environment and geodatabases were created to store them. The dataset examined within ArcGIS necessitated a balance in the coordinate system as well as building attribute tables for the database. Where necessary, data management tools such as "project", "union" were used to modify the data in terms of its spatial extent to prepare them into a form in which they can be used for analysis.

The next step is the analysis; this involves the determination of the logic and sequence of operations, the determination of the workflow of the project and using the right set of tools for the geoprocessing task. The application of the geoprocessing tools with the input dataset enables the processing of the data, which then yields a new dataset that serves as the input for the next procedure in the workflow.

The study interpreted the final output which represented the results, these were polished and the maps were presented in the result chapter of this research. Figure 3.10 shows an example of the model used to determine coastline changes within the Lagoon coastline dataset.

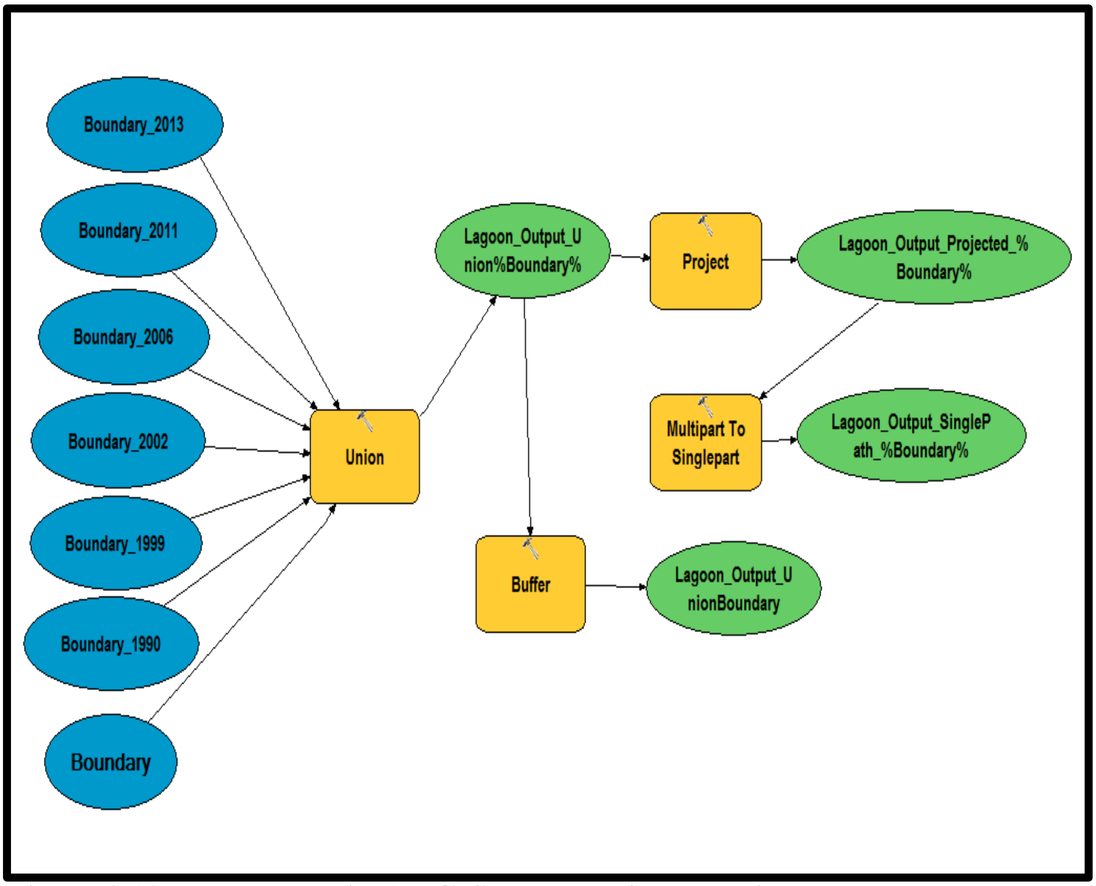


Figure 3.10: Model used in ArcGIS to determine coastline changes

An important task to the analysis of the research in this section is finding the right tools needed through all the analysis stages, creating and customising the tools in a toolbox. The index and search tabs within the Arctoolbox were used to find the location of the tools. For efficiency workflow in this section of the study, customise a toolbox was created because the tools were meant to be used many times in the course of the analysis done in the section. The toolbox created for this analysis was named "Lagoon_CoastlineChanges", the tools needed for the analysis were then transported from the system toolbox of the Arctoolbox into this newly created toolbox.

3.9 Lagoon stratification

To evaluate the Lagoon stratification under different conditions of tidal ranges and river inflow, the Lagoon Richardson number R_i (Dyer, 1997; Fischer *et al.*, 2013) was computed. The Richardson number expresses the ratio of the potential energy gain due to freshwater discharge to the mixing power of tidal currents. Thus the computed R_i

represents the ratio of bouyancy forces to vertical turbulent force and it determines the nature of mixing in any water body (Dyer, 1997). This principle was applied in studying the turbulent nature of the Lagoon during the dry and wet seasons, when the rate of freshwater inflow varies as a result of variations in rainfall. This was defined in the research as:

$$R_i = \frac{{-g}/{\rho} \times {\delta_\rho}/{\delta_Z}}{({\delta_\mu}/{\delta_Z})^2} \qquad \text{Equation 3.39}$$

Where g = Acceleration due to gravity

$\rho =$ Average density between two depths

$\delta_\rho =$ Density at upper depth – density at lower depth

$\delta_\mu =$ Velocity at upper depth – velocity at lower depth

$\delta_Z =$ Upper depth – lower depth

If R_i is greater than zero, the Lagoon is considered to have stable stratification, hence no mixing. If R_i is less than zero the Lagoon is considered to have unstable stratification, hence the dominant effect is shear and the Lagoon is mixed. If the value of R_i is equal to zero, there is neutral stratification in the Lagoon, the water is partially mixed.

The water column stability was analysed using buoyancy frequency (N), this was calculated in all the locations where R_i was computed, hence N is defined as:

$$N = \left(\frac{g}{\rho}\frac{\delta\rho}{\delta z}\right)^{\frac{1}{2}} \qquad \text{Equation 3.40}$$

Where ρ = the measure of density of water

g is acceleration due to gravity

δ_ρ = Density at upper depth – density at lower depth

δ_Z = Upper depth – lower depth

The characteristics of the whole flow in the Lagoon was analysed using R_i. This was complemented by means of the Buoyancy frequency (N). Part of the results show N values as a function of the layer's depth for all the locations where data was collected on the Lagoon. The data used in this section was collected in two different seasons (dry and wet) on the Lagoon. The current meter data discussed in section 3.6.3 forms the basis of the data used in the computation of the Richardson number. Figure 3.10 depicts the experimental design as it was carried out in this study during field observation. The assumption made in the design was that acceleration due to gravity (g) is the same (9.8m/s^2) at various depths h_1, h_2 and h_3. The value of d_1, d_2 and d_3 were different at various spatial locations depending on the depth of the Lagoon water at each location. It was not necessary that the d values be the same at different measurement locations.

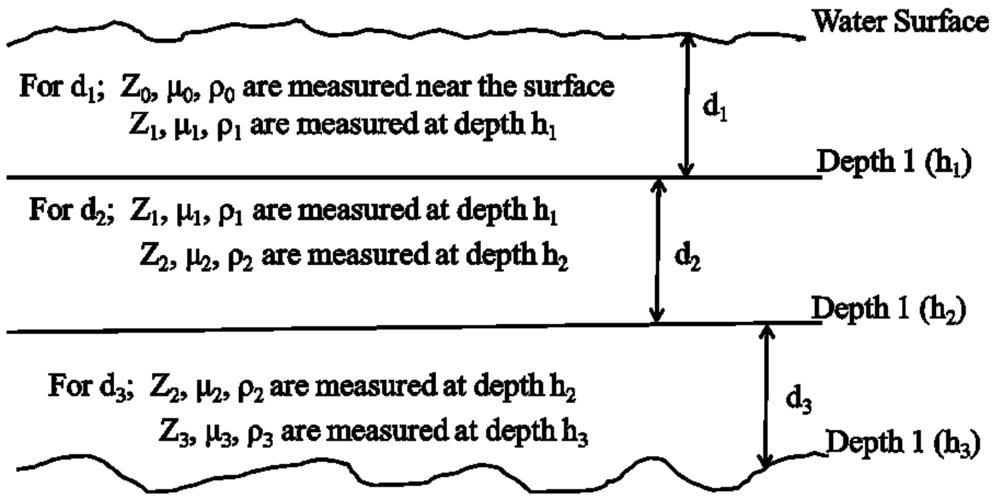


Figure 3.11: Design for the Richardson Number Experiment (Author)

Furthermore, stratification was computed at each spatial location where measurement was carried out in the Lagoon to see the effect of vertical mixing on the Lagoon water profile; this was carried out using the simple model:

$$\omega = \frac{\delta_S}{\hat{S}} \qquad \text{Equation 3.41}$$

Where ω = Water stratification

δ_S = difference between salinity at the upper layer and salinity at bottom layer

$\hat{S}$ = mean salinity of the water profile

Inherent to this aspect of the research was the assessment of the Lagoon water mixing that enabled the examination of the spatial pattern of the Lagoon stratification in the dominant two seasons in the region. Three of the data parameters collected by current meter in the Lagoon were adopted for the actualisation of the results under this section; these were density, velocity flow and water depth at various points of measurement. A summary of the steps and method to achieve this is as follows

- Collection of data from the study location using current meter equipment, bearing in mind the design in Figure 3.11. The parameter includes velocity flow, depth and density of water at each location of measurement.
- Processing of data, this involves downloading the data and storing it in Excel format (xls). Excel PivotTable was then used to do the sorting and arrange the data according to spatial location and the period of collection.
- Next step was the computation of the Richardson number using the Dyer's model in Equation 3.39 and the water stratification using Equation 3.41.
- The computed R_i and ω were plotted in ArcGIS with the coastline map of the Lagoon, this showed the spatial distribution of the computed R_i and ω values.
- With the Analyst tool from the ArcGIS, analysis was done based on the four tidal strengths measured during data collection.

3.10 Lagoon flushing time

The flushing behaviour of the Lagoon was investigated using freshwater fraction method. This was carried out by computing the time it took for the system to flush the saline water and replace it with the fresh water intrusion from inland. The flushing variability of the lagoon depends largely on the channels (artificial and natural) from inland which connect it with inflow of fresh water. In computing the system flushing time of the Lagoon in this study, the data collected using the current meter was used as primary data to compute the parameters that led to the final computation of the flushing time, the process was as follows:

Flux rate (Brenes et al., 2007) into the Lagoon through the inlets were calculated using the measured surface velocity. The cross sectional area of each of the inlets was calculated from depth of the channel and the GPS coordinates of the two ends of the inlet mouth. This was defined as:

$$Flux\ (\lambda) = c * A_T \qquad \text{Equation 3.42}$$

Where λ = flux

c = Surface velocity

A_T = Cross sectional area of the inlet

The Lagoon volume at flood tide was calculated as:

$$Total\ surface\ area * Average\ depth\ at\ flood\ tide \qquad \text{Equation 3.43}$$

From Dyer (1997) a model for the fractional fresh water concentration was defined and computed as

$$f = \frac{S_s - S_n}{S_s} \qquad \text{Equation 3.44}$$

Where f = fractional fresh water concentration

S_s = salinity of undiluted sea water

S_n = mean salinity in any part of the Lagoon

Finally, the flushing time for the Lagoon was calculated using the results from Equations 3.42, 3.43 and 3.44, hence flushing time was expressed as:

$$T_f = \frac{fV}{\lambda} \qquad \text{Equation 3.45}$$

Where T_f = flushing Time

f = fractional fresh water concentration

V = volume of the system

λ = flux

The flushing time was computed for both the dry and the wet season and compared so as to examine the nature of the Lagoon entrance during dry and wet seasons and its exchange capabilities with the open sea. The result also suggested how long effluents from the surrounding industries stay within the Lagoon.

3.11 Spatial particle characterization

Sediment grain size is very basic to the characterisation of any lagoon bed-form; it is the major principal feature of sedimentary deposits (Poppe *et al.,* 2004). The spectra size bed-surface of sediment grain from different depositional environment differs due to the particle size distribution (PSD) of parent material, hydrodynamic characteristics of deposition and selective and destructive transport processes (Friedman & Sanders, 1978; Watson *et al.,* 2013). In the recent time, it has been discovered that biologically active and fine grained sediment form abundant sedimentary deposit on earth surface and mixed mud-sand controls majority of the coasts, lagoons and estuaries, deltas (Parsons *et al.,* 2016). At any spatial bed-form in the coastal water, PSD reveals the characteristic range of energy conditions that influence transportation and deposition accumulation (Watson *et al.*, 2013). Thus, analysis of PSD is very essential study in any lagoon because it helps in transport and depositional processes related to sedimentary deposit. From this analysis, further information about processes in watershed and morphological setting of the depositional area can be derived.

The importance of PSD in the case study area led to carrying out two basic empirical tests which help to determine PSD and the settling velocity on the Lagoon. The two functional empirical tests used are Andreasen pipette experiment for determination of PSD and Hindered settling experiment for determination of particle settling velocity in the Lagoon. The processes for the experiments are detailed below.

3.11.1 Andreasen pipette experiment

The aim of this experiment is to determine the grain size distribution of fine grained sediment of the Lagoon by sedimentation method.

Muddy water samples are collected at various spatial locations on the Lagoon during the field data collection. The samples were preserved until the time of carrying out the experiment in the laboratory; the following are the steps in carrying out the experiment:

- From the samples collected (Figure 3.12) in each location, a suspension of muddy sediment with a concentration of about 5g/l is provided
- For each experiment on each sample location, weigh a Petrie dish and marked (named) with the coordinate of the location and record the temperature (T; units °C) of the suspension.
- Shake the suspension and immediately take 20 ml sample with pipette, the sample is decanted into a pre-weigh evaporating dish. When dried and re-weighed the sample so as to allow for calculation of the initial concentration of the suspension at time (t) = 0.

- The suspension is stirred again, and when the major part of the turbulence has died away and sediment is beginning to settle uniformly, start the timer. Take a pipette sample at 30 seconds; decant the sample into a Petrie dish.
- Stop the clock, stir the sample again and repeat sampling sequences taking samples at time (t) = 1 minute, 3 minutes and 5 minutes. After 5 minutes you don't need to stop the clock and restart. Take further samples at 10, 20, 30 and 30 minutes. Dry and weigh the samples then record all data.

Figure 3.12: Sample of sediment specimen collected on the Lagoon

At each time interval, the measurement of time taken by particle to settled (W_s is settling velocity) is taken over the sample depth of 10cm. The extracted sample will contain particles of sizes d or less than d. At each time increment, particle size (d) and cumulative weight (P) can be computed using the formulae below:

$d^2 = F^2 \times (W_s)$ Equation 3.46

$= F^2 \times \left(\frac{depth\ of\ sampling\ (cm)}{elapse\ time\ (min)}\right)$ Equation 3.47

$F = -0.148T + 16.55$, T is temperature Equation 3.48

Cumulative weight, $P\ (t)$, is calculated from:

$$P(t) = \frac{(W_d(t) - W_c(t))}{(W_d(t=0) - W_c(t=0))} \times 100 \qquad \text{Equation 3.49}$$

Where W_c is the dish weight and W_d is the dis plus sediment weight

The results of the experiments on samples from different location are plotted as cumulative curve of sediment grain size distribution (P versus d). For further information on the experiment, see Manning *et al.* (*in press*).

3.11.2 Hindered settling

The main aim of setting up this experiment is to measure the settling velocity of interfaces within a suspension in the Lagos Lagoon and to analyse and compare results in relation to the properties of the suspension and fluid. The following steps were followed to carry out the experiment:

- Like the Andreasen experiment, muddy samples collected at various spatial locations are prepared in suspension form inside graduated cylinders (Figure 3.13) marked differently with coordinates of each of the locations in order to differentiate their results.
- The initial height of the water column (h_0) and of the bed layer if it is apparent.
- Each of the suspension samples are shaking and start a synchronised stopwatch.
- The elevation (h) of the interface falling from the surface as well as the one rising from the bed (if present) are recorded as a function of time (t). 1 minute intervals of recording were used until 15 minutes, and then 2 minutes intervals. See Manning *et al.* (*in press*) for further information on the empirical test.

From each result, height is plotted against time for all suspension sample columns and settling velocity of the interface for each column is estimated by linear regression.

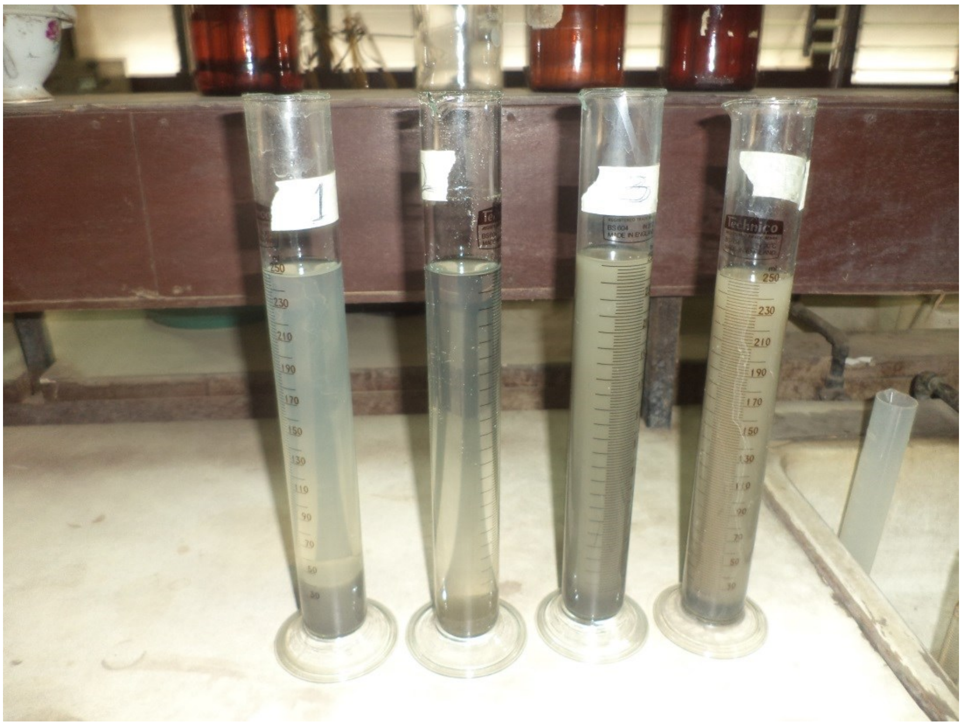


Figure 3.13: Sediment specimen from the Lagoon prepared in suspension form. The experiment took place at the Department of Civil and Environmental Engineering Laboratory, University of Lagos

3.12 Stage Three: Long time study and demonstration of transferability

Short term variation data were employed in this study because of the specific time allotted to finishing the research, hence it was impossible to wait for a longer time scale, continuous dataset before the study could be completed. Moreover, it would have been great using historical data, but there was no previous continuous or short term data for this area was available. Therefore, the collected data within the time frame of the research was maximised to obtain optimum results.

Using the temporal term scale data to investigate the degree of changes on a Lagoon where long-term and temporal drivers contribute to the changes in the system over time, suggest the need to gather a long-term data on the Lagoon so as to improve the degree of efficiency of any model being used for evaluation and also for improving investigations resulting from the short-term data. Transferring these baseline models and results of the investigation on the Lagoon will help to build a robust model that could both simulate and predict future changes in the Lagoon.

Furthermore, after a series of validations and ascertaining of the trend of changes in the Lagoon, the various investigation methods could be transferred to other lagoons, especially in the tropic regions, to study the trend of hydrodynamics and morphological changes in them over time; and so could be used for the prediction of future changes. The long-term transferability of this research will form one of the basic future research areas, especially for the Lagos Lagoon.

3.13 Scope and limitations of the methodology

The research was limited by some factors. Firstly, there was the unavailability (high quality, repetitive morphological survey, short-term or long-term hydrodynamic) of data covering the area of study either from government institutions or private companies that could be fed into the variables of the models that were used in the research. Due to this, data collection from the field was embarked upon. Secondly, the lack of instruments (current meter, CTD) and a comfortable boat with a winch for data collection at the research institution where the research field was based posted another challenge and slowed down data collection period. To overcome this, the instrument (current meter) used for the research data collection was hired from Plymouth University and transferred to Nigeria at two different occasions.

In terms of morphological changes, the research was limited in terms of the accuracy of the image data used and the challenge of cloud cover. For a more detailed study, image data with higher resolution (IKONOS, QuickBird, SPOT 6-7, and World View–3) would have been more appropriate, however, these are very expensive to purchase. Also, gathering data that covers the entire area of a large Lagoon like the one involved in this study is difficult considering factors like lack of appropriate instrument, cost and security threat that are very prevalent in the study location. Hence, area of data coverage was limited to the available resources that can cover. Lastly, to the best of the authors knowledge there was no either historical or scientific evidence of any data used for assessment of morphological and hydrodynamic progressive study towards the sustainability of the Lagoon. This in itself highlighted gaps in the Lagoon management and provided evidence that there had been no study of the morphological and hydrodynamic changes on the Lagoon that has been done on the system so far.

3.14 Summary

Chapter three gave detailed explanations of the methods adopted in the research. The methods were approached in three different stages, the first stage details the preliminary study which includes examination of the research area, appropriate data requirements, investigation into the available data in the study area, and preliminary data acquisition. The second stage presents the body of knowledge that give procedures for data acquisition design, data processing, application and modelling. These were employed to estimate the morphodynamic changes in the study Lagoon. It expressed the two main types of data used, the visible infrared satellite data (Landsat) and in-situ hydrodynamic data. However, the Chapter concludes with stage three which reflects on possible long term study and demonstration of transferability.

3.15 Conclusion

This chapter has given detail step by step methods that were employed in order to accomplish the main aim of the study using the outlined objectives set up for the research. Although, a functional (existing) approach was used in order to generate research findings, however, the application was very new in the Lagoon. This will enhance the researchers in that region to see more areas that could be explored in terms of new research that could be conducted toward the management and sustainability of the Lagoon.

CHAPTER FOUR
MAPPING OF SPATIAL VARIABILITIES IN LAGOON ECOSYSTEM

4.1 Introduction

The chapter presents the results of the changes in the Lagoon wetland ecosystem from 1984 until 2015 using satellite data (Landsat 1984 to 2015), population data of Lagos State, and meteorological data (rainfall temperature and relative humidity). The chapter reiterates the study location, Lagos Lagoon, relative to its position along the coastline of Nigeria. It anchors the results of the depletion in the various classifications of the wetlands present in its ecosystem. Furthermore, the results of the different rates of depletion of the Lagoon wetlands were analysed with the rate of urbanisation evolution in terms of population growth which impedes the natural existence of the wetland. However, a critical analysis was made on the evolutionary changes around the lagoon using LST and NDVI as one of the significant indicators that reveals consequential changes on the Lagoon ecosystem. Such changes are disclosed by the results of the various analyses that were carried out on the quantity of the mangrove, swamp, vegetation and built up area present on the Lagoon ecosystem over the different time scales of the study. Lastly, the results of the investigation of the changes along the Lagoon coastline due to urban expansion was presented in this section which depicts different maps generated from the model used by the author to investigate the Lagoon coastline changes.

The various results achieved from this section ascertain the impact of urbanisation on the Lagoon environment and the degree of changes that has taken place over a period of thirty one years within which the population has increased incessantly in the city of Lagos. This suggests that the natural existence of most mangroves, vegetations and swamps in the

Local Governments' Areas (LGA) that surrounds the Lagoon has been impacted upon and this must have affected the natural balance of the Lagoon coastline.

4.2 Lagos Lagoon Coastal Profile

The study location for this research is the Lagos Lagoon, located in Nigeria. Nigeria is located in western Africa bounded in the west by Republic of Benin, at the southern part by Atlantic Ocean, in the east by Cameroun and in the north by Niger and Chad (Figure 4.1). Lagos (Figure 4.2) is situated at the extreme south western part of Nigeria and in the heart of the city is Lagos Lagoon. Lagos is bounded within latitudes 6° 23'N and 6° 41'N and longitudes 2° 42'E and 3° 42' (Adelekan, 2010). The Lagos Lagoon boundaries are outline by Uduma-Olugu & Adebamowo (2015) as: bounded by Five Cowrie Creeks at the south, the north is bordered by Ikorodu LGA, western margin is bordered by mainland and the east boundary is bordered partly by mainland and partly by Lekki lagoon (Figure 4.3). The Lagoon sediment range between mud, sandy mud, muddy sand and sand (Nkwoji *et al.,* 2010)

The Nigerian climate is dominantly tropical, characterized by high temperatures and humidity and likewise marked by wet and dry seasons. At the coastal area where the Lagos Lagoon is situated, annual rainfall ranges approximately between 1,500 and 4,000 mm which are almost close to the rainfall seasonality in the Niger Delta that is close to the region (Adejuwon, 2012). Between late November and May during the dry season, the sea surface temperatures range from 27°C to 28°C, while during the wet season from June to late October, the range is between 24°C and 25°C (Ojeh, *et al.*, 2016). Around the locality of the Lagos Lagoon, the surface water is typically oceanic surface water of the Gulf of Guinea with salinity generally less than 35 part per thousand (ppt) in January to March and these are also less than 28 – 30 part per thousand (ppt) during raining season in June to September. Low salinity values are as a result of influx of fresh water from various rivers from the upland that empty into the Lagoon.

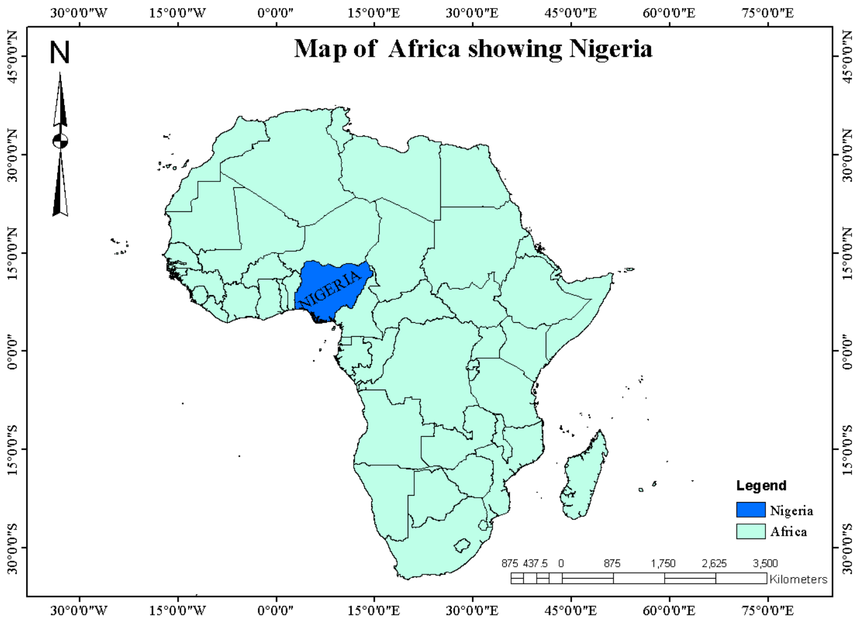


Figure 4.1: Map of Africa showing Nigeria. Adapted from ESRI, (2014)

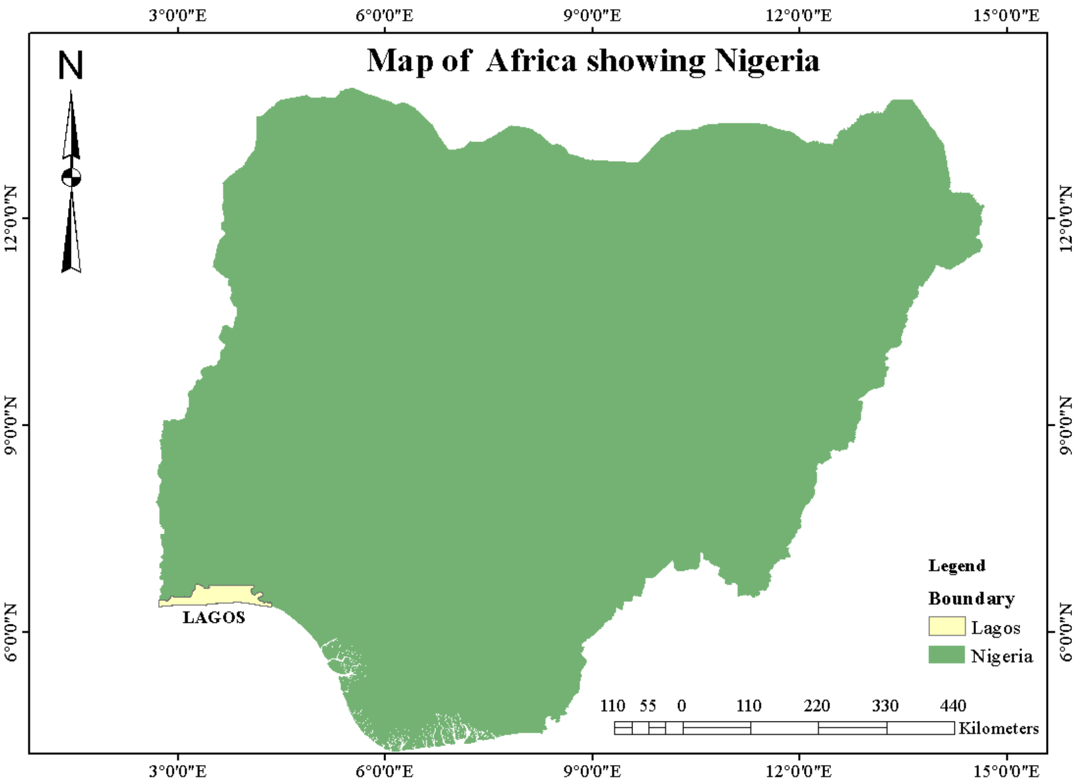


Figure 4. 2: Outline of Nigeria showing Lagos state – Adapted from Global Administrative Areas, Accessed December 2015 (http://www.gadm.org/)

4.2.1 The Location of Lagos Lagoon

The Lagoon is located in the heart of the city of Lagos (Figure 4.3) with the southern part bounded with Barrier Island which separates the Lagoon from the Atlantic Ocean. The island is the commercial centre for the city of Lagos; the island has a very high population of people living and trading in Lagos city. Out of the twenty LGA in Lagos, eight of them border the Lagos Lagoon by the south, west and north directions. All the eight LGA have swamp and mangrove in different proportions.

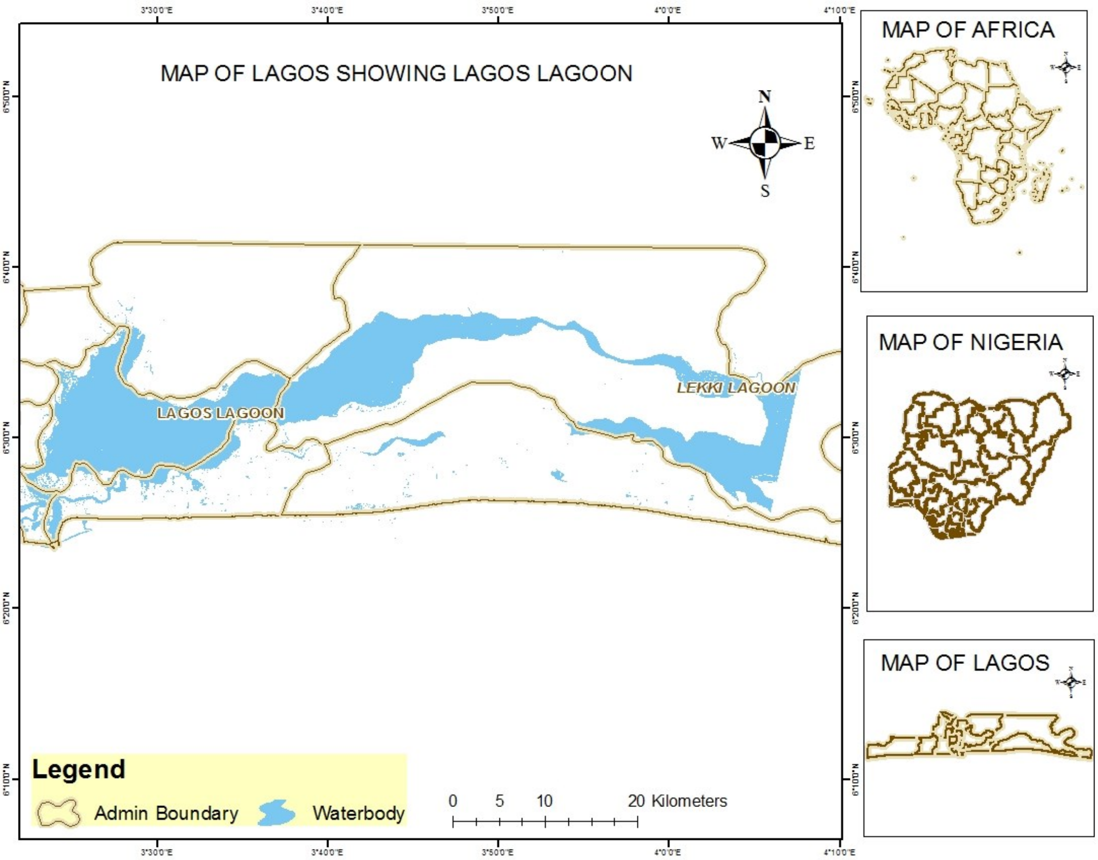


Figure 4.3: Map of Lagos showing Lagos Lagoon. The map origin was from Global Administrative Areas, it was uploaded into ArcMap in order to add the symbols and other features that make it a complete map. Adapted from Global Administrative Areas, Accessed December 2015 (http://www.gadm.org/)

4.3 Case Study

In this section, particular interest was focused on the Lagoon ecosystem that was covered in the study location the boundary of the covered area on the Lagoon was approximately between latitude 6° 25' and 6° 40' and longitude 3° 20' and 3° 55'. During data hydrodynamic field data collection the boundary was reduced on the Lagoon water body. The ecosystem was classified into five (swamp, mangrove, built up, bare land, and vegetation), to conveniently see the degree of disappearance or increase in each over the years that the data cover. This provides the opportunity to calculate the percentage rate of loss in each classification per year in each of the LGA that surround the Lagoon and hence the total loss of mangroves and wetland as a result of increased urbanisation between 1984 and 2015. The assessment of the changes on the wetlands and mangroves around the Lagoon was necessary because they serve as medium of absorption between the land and the Lagoon; they provide a unique natural balance to the Lagoon coastline. They also serve as a medium that mediates between the activities in the Lagoon and the sea. Hence changes in these classifications have a direct effect on the Lagoon.

4.4 Observed changes in Mangroves

It was observed that the mangroves were declining yearly around the Lagoon. The mangrove loss was calculated as area-wide mangrove changes from 1984 to 2015 and estimated in each of the eight local government council that bounded the Lagoon (Tables 4.1 and 4.2). The highest decline in mangroves within 1984 to 2002 was experienced in Epe where it declined at 0.47km^2 per year followed by Eti-Osa LGA at the rate of 0.33km^2. Conversely between 2002 and 2015 an increased depletion in mangroves was recorded in Ibeju-Lekki LGA at 1.97km^2 followed by Eti-Osa at 0.57km^2 deficits per year (Table 4.3). The exponential increase suggests urban expansion which leads to the encroachment of the natural mangroves around the Lagoon ecosystem. From 1984 to 2015, Ibeju-Lekki showed a total of 38.39% (Table 4.3) change out of the hundred percent mangroves in the area ecosystem. Apart from this, a sharp depletion in mangroves occurred in the LGA between 2002 and 2015 (Figures 4.4 and 4.5) - this suggests that the region experiences a high rate of urbanisation. Conversely, other LGA experience steady depletion in mangroves except Lagos Island and Lagos Mainland that show almost no change in mangrove area (Figure 4.5). The main driver of the depletion in mangroves both in the northern and southern region of the lagoon can be ascertained from the degree of increase in built-up area as urbanisation increase, and hence the urban development is principally the driver of the conversion. Almost all the mangroves in the western part of the Lagoon have been replaced with urban development as at 2015. This is an indication that there is excessive demand for space which suggests that human population around the Lagoon ecosystem is increasing hence increase human activities which bring about pressure or stress on the Lagoon is assumed to have been taken place.

Table 4. 1: Extents of swamps and mangroves per LGA in 1984

LGA	Swamps (km^2)	Percentage of swamps	Mangrove (km^2)	Percentage of mangroves
Apapa	0.20	0.05	3.32	2.75
Epe	132.22	32.84	25.14	20.85
Et-Osa	38.69	9.61	19.76	16.38
Ibeju-Lekki	124.39	30.89	29.72	24.65
Ikorodu	98.10	24.36	23.62	19.59
Kosofe	8.94	2.22	17.87	14.82
Lagos Island	0.00	0.00	0.24	0.20
Lagos Mainland	0.13	0.03	0.92	0.76
Total	402.66	100.00	120.58	100.00

Table 4. 2: Extents of swamps and mangroves per LGA in 2015

LGA	Swamps (km^2)	Percentage of swamps	Mangrove (km^2)	Percentage of mangroves
Apapa	0.05	0.02	0.86	1.62
Epe	116.83	40.62	13.75	25.93
Et-Osa	6.74	2.35	6.45	12.17
Ibeju-Lekki	117.91	41.00	3.79	7.14
Ikorodu	43.12	14.99	15.73	29.67
Kosofe	2.93	1.02	12.10	22.81
Lagos Island	0.00	0.00	0.01	0.02
Lagos Mainland	0.01	0.00	0.35	0.66
Total	287.60	100.00	53.03	100.00

Table 4. 3: Coverage Area of Mangrove by LGA from 1984 - 2015

LGA	1984 (km^2)	2002 (km^2)	2015 (km^2)	Change (km^2) (1984-2002)	Change (km^2) (2002-2015)	Change (km^2) (1984-2015)	% Change (1984-2002)	% Change (2002-2015)	% Change (1984-2015)
Apapa	3.32	2.29	0.86	1.03	1.43	2.46	5.03	3	3.64
Epe	25.14	16.63	13.75	8.51	2.88	11.39	41.57	6.04	16.86
Eti-Osa	19.76	13.86	6.45	5.9	7.41	13.31	28.82	15.55	19.7
Ibeju-Lekki	29.72	29.41	3.79	0.31	25.62	25.93	1.52	53.76	38.39
Ikorodu	23.62	21.28	15.73	2.34	5.55	7.89	11.43	11.65	11.68
Kosofe	17.87	15.83	12.10	2.04	3.73	5.77	9.97	7.82	8.54
Lagos Island	0.24	0.19	0.01	0.05	0.18	0.23	0.24	0.38	0.34
Lagos Mainland	0.92	1.21	0.35	0.29	0.86	0.57	1.42	1.8	0.85
Total	120.59	100.07	53.04	20.47	47.66	67.55	100	100	100

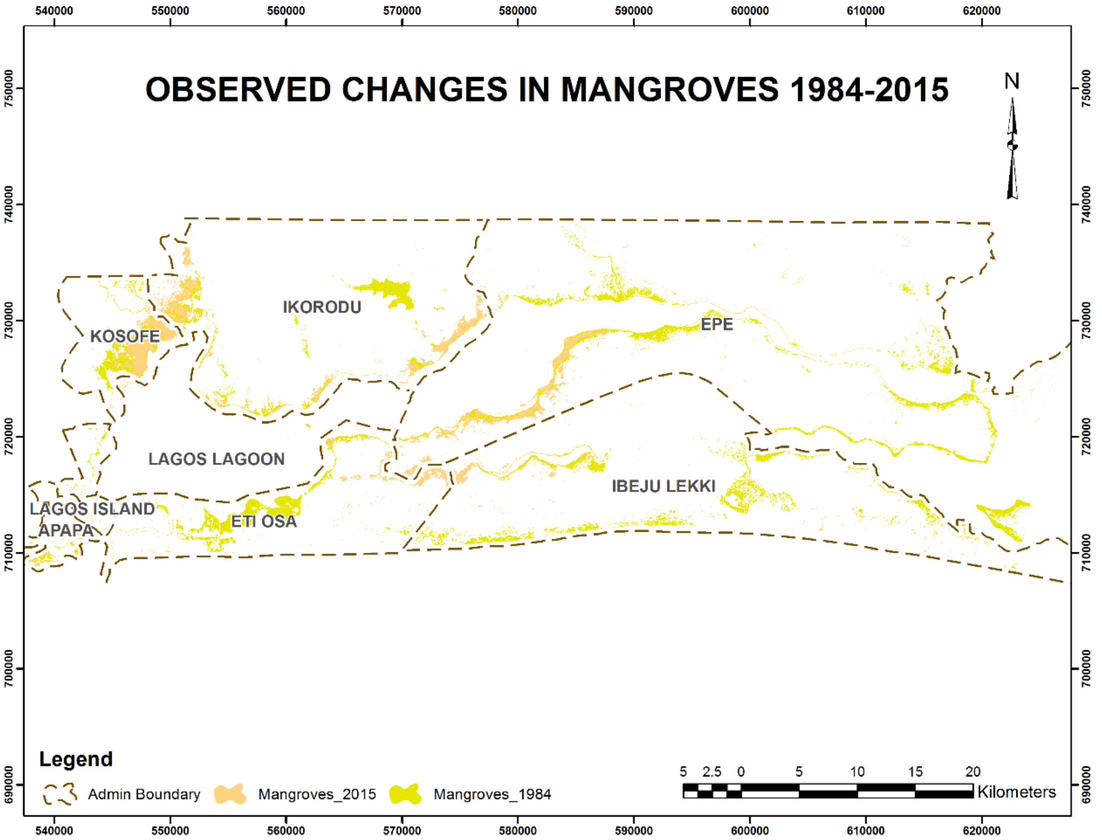


Figure 4. 4: Map of Lagos Lagoon Ecosystem showing changes in mangroves between 1984 and 2015

Consequently, Ibeju-Lekki experience the highest mangrove depletion between 2002 and 2015 compare to 1984 to 2002, meaning that the rate of urbanisation was very high between 2002 and 2015. By implication the ratio of depletion in 2002 compare to 2015 is approximately 1:35. However, in Epe local council mangrove depletion was highest between 1984 and 2002 with a percentage change of approximately 42%. Conversely, Ikorodu recorded almost the same rate of mangrove depletion over the study period. The fast disappearance of the mangroves in all the LGA suggests encroachment into the wetland for possibly settlement reason. As at 2015 (when the data for the study area was obtained) only 53.04km^2 of mangroves remain in all the LGA against 120 km^2 that was available in the entire study area in 1984. In overview, approximate mangroves of 2.18km^2/year is depleted in the entire Lagoon ecosystem, this suggests if the rate of depletion is maintained, the entire mangroves in the system will be totally depleted in the next 24 years, that is the year 2039.

Most importantly, the mangroves in any ecosystems protect vulnerable coastlines from wave action because they hold the soil together and prevent coastal erosion. Among other advantages of mangroves to the lagoon ecosystem is that it shields inland areas during storms and minimises damage. Conversely, since a large proportion of all the mangroves in all the LGA that surround the Lagoon has been encroached upon and turned to built-up and impervious area, the immediate inland environment around the Lagoon is highly vulnerable to flooding and erosion which as time goes on will endanger all the dwellers in such communities. Figure 4.7 shows a typical outcome of flooding in the Lagos Island area. This incident occurred in 2014 and was reported by Nigerian Vanguard newspaper (February 2014). The uncontrolled depletion in the mangroves around the Lagoon endangers the dwellers and other habitats that survive on the mangrove region of the Lagoon.

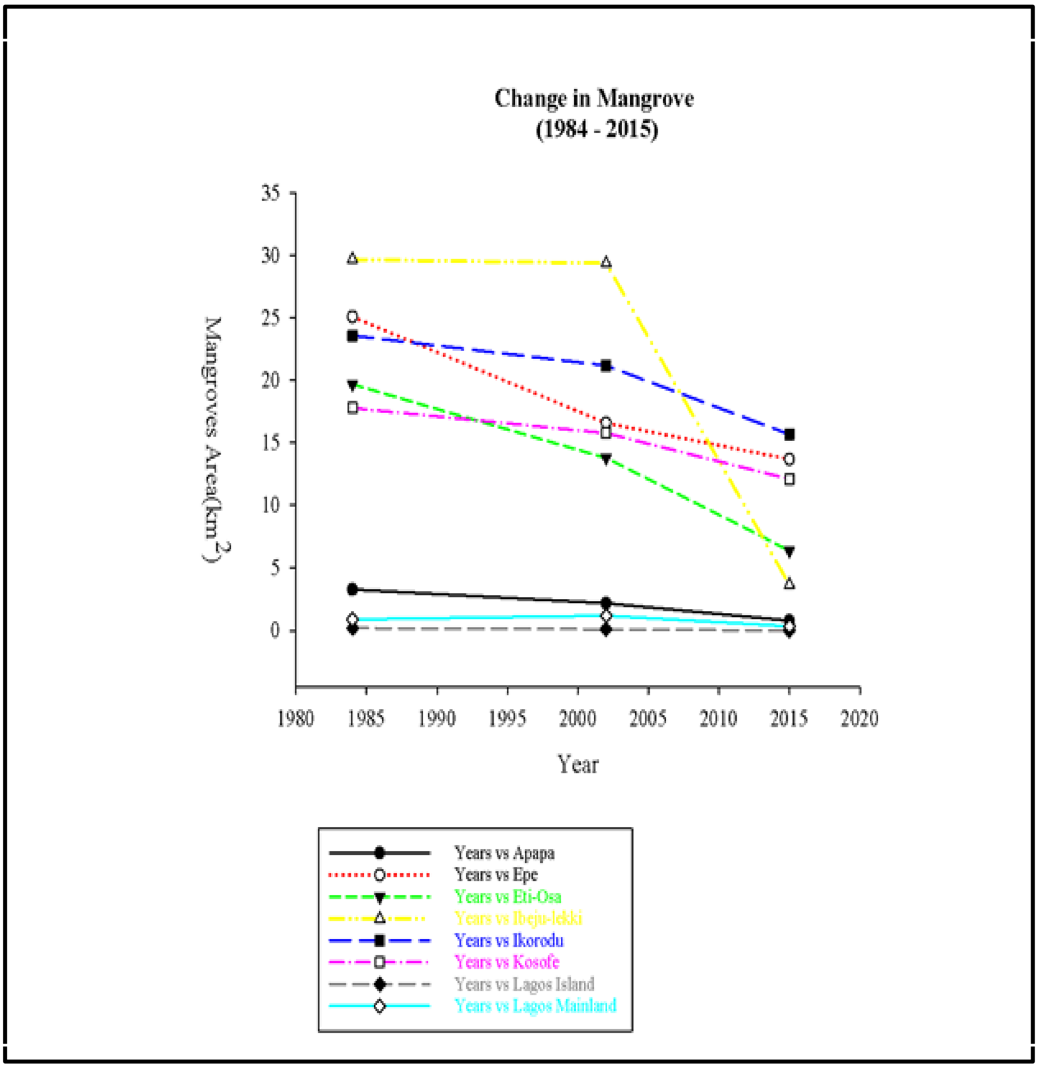


Figure 4. 5: Graph depicting trend of changes in mangroves by LGAs between 1984 and 2015

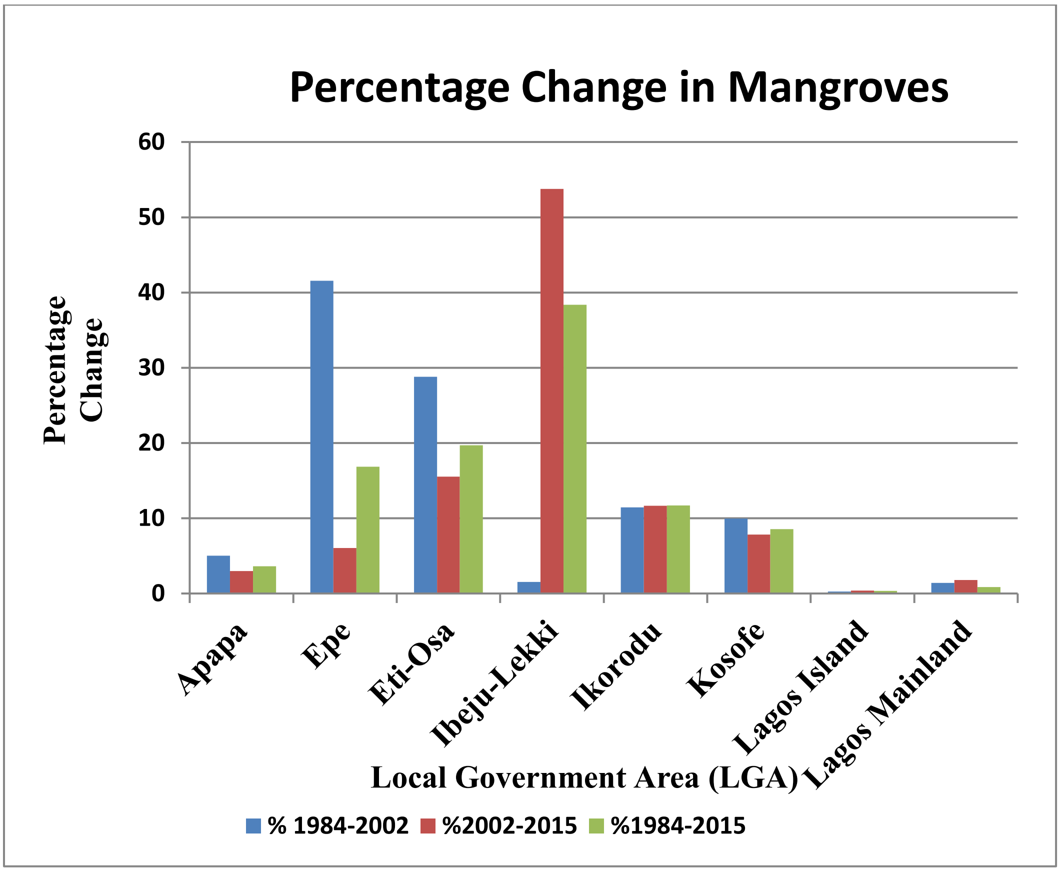


Figure 4. 6: Percentage change in the mangroves in the eight LGA around the Lagoon

Figure 4. 7: Flooding in Lagos Island, one of the LGA where between 1984 to 2015 about 96 percent of the total mangroves in the local council have been depleted and replaced by built-up areas as a result of fast urban growth [Source: (Akoni, 2014)]

Ecologically speaking, all the plant and animal species that find shelter in the mangroves have been destroyed. This has an adverse effect on fish production in the Lagoon because mangroves serve as fish nurseries, and hence a destruction of this habitat results in very low production of fish.

4.4.1 ANOVA Analysis for change in Mangroves by Local Government Area

ANOVA analysis was performed on the changes on the mangroves that exist around the Lagoon between 1984 and 2015. Hypothesis (Null and Alternate) were set thus:

- Null hypothesis (H_0): $\mu = 0$ (there is significant difference in the mean of the mangrove coverage by LGA between 1984 and 2002; 2002 and 2015; 1984 and 2015).
- Alternate hypothesis (H1): $\mu \neq 0$ (there is no significant variation in the mean of the mangrove coverage by LGA between 1984 and 2002; 2002 and 2015; 1984 and 2015).

The decision rule was set with significant level (α) at 95% in order to the probability of rejecting or accepting the true hypothesis.

Based on the assumption of Obiefuna *et al.,*(2013), changes are most likely to take place in the coverage area of the mangroves in the LGA around the Lagoon; analysis of variance ANOVA analysis as statistical tests were performed on the mangrove data of 1984 – 2015. The ANOVA table (Table 4.4) decomposes the variances of changes into two components: a between-group component and a within-group component. The F-ratio, which in this case equals 0.86, is a ratio of the between-group estimate to the within-group estimate. The P-value of the F-test (0.5611) is greater than 0.05, hence the Null hypothesis is rejected and accept the alternate hypothesis; this suggests that there is not a significant difference between the mean changes from one level of LGA to another at the 95% confidence level (Figure 4.8). This result led to further statistical tests based on changes from year to year in some LGAs.

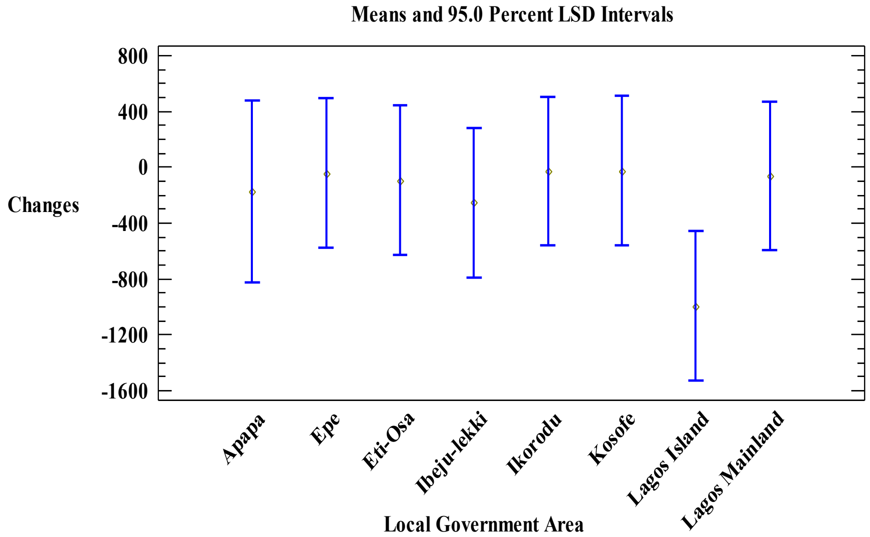


Figure 4. 8: Analysis of variation between mean changes from one level of LGA to another at 95% confidence level

Table 4. 4: ANOVA Table for Changes by LGA (the 8 LGAs)

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	2.24081E6	7	320116.	**0.86**	**0.5611**
Within groups	5.61323E6	15	374215.		
Total (Corr.)	7.85404E6	22			

Further ANOVA statistical testing was carried out on some LGAs on the assumption that there is a depletion in mangroves year in year out (for instance 1984 to 2002) using the result from Figure 4.5. Based on this, Epe, Eti-Osa, Ibeju-Lekki and Ikorudu LGAs were taken as areas that experience the highest mangrove depletion. The test was carried out in order to scientifically ascertain if there is truly significant variation in the mangrove coverage from 1984 to 2015.

The hypothesis for the test was set as that of section 4.3.2 at 95% confidence level. The ANOVA table (Table 4.5) shows the result of the statistical test where the differences in the mean values among the treatment groups are greater than would be expected by chance; moreover the F-ratio which in this case equals 21009.291 is a ratio of the between-group estimate to the within-group estimate and the computed p-value (1.41624E-19) is far less than 0.05; this indicates that there is a statistically significant changes.

Table 4. 5: ANOVA Table for Changes in the four LGA that was assume to have excessive mangrove depletion

Source of Variation	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	9429193.809	4	2357298.452	**21009.291**	**1.41624E-19**
Residual	1122.027	10	112.203		
Total (Corr.)	9430315.836	14			

Pairwise multiple comparisons was conducted under the ANOVA test using the Holm-Sidak method, the test compares each of the LGAs with years, it also compares LGA versus LGA but the latter was discarded because interest was focused on the interaction between each of the LGAs and the year. The result of the pairwise multiple comparisons are shown in Table 4.6.

Table 4. 6: Pairwise multiple comparison at 95% confidence level

Comparison	Diff of Means	t	P-value (< or > 0.05)	P < 0.05
Years vs Eti-Osa	1987.033	229.747	< 0.001	Yes
Years vs Epe	1981.867	229.149	< 0.001	Yes
Years vs Ikorodu	1980.167	228.953	< 0.001	Yes
Years vs Ibeju-Lekki	1979.400	228.864	< 0.001	Yes

Inferring from the result of Table 4.5, it has been scientifically proved that there is significant changes in the mangroves of the four LGA around between 1984 and 2015. The indicator for the change (depletion) is assumed majorly to be the urban growth around the Lagoon. The relative depletion in mangrove and swamp between 1984 and 2015 can be seen being replaced majorly with built-up areas (Figure 4.10).

4.4.2 Results: Changes in Mangrove coverage area by years

Although the ANOVA test did not show significant difference between the mean changes from one level of year to another at 95% confidence level, this does not indicate that there were no variations in the mangrove coverage area by years. However, using Levene's variance check test there were statistically significant differences among the standard deviations of the parameters. The statistic display on Table 4.7 tests the null hypothesis that the standard deviations of changes within each of the three levels of years are the same. P-value for the variance check test is less than 0.05 (0.0137), hence there is a statistical significant difference among the standard deviations.

Further correlation when comparing the years shows that the p-values of 1984/2015 and 2002/2015 are less than 0.05, indicating that there is a significant variation in the mangrove coverage between 2002/2015 and 1984/2015. Conversely, the p-value of the comparison between 1984/2002 was greater than 0.05. This demonstrates that there is no significant change in the mangrove coverage area between 1984 and 2002. This suggests that urban growth was very high around the Lagoon ecosystem within the period 1984/2015 and 2002/2015 but though there may be urban growth in 1984/2002, it was not very significant like the other two periods.

Table 4. 7: Levene's Variance Check within

	Test	P-Value
Levene's	5.35267	**0.0137455**

Comparison	Sigma1 (σ_1)	Sigma2 (σ_2)	F-Ratio	P-Value
1984 / 2002	21.8111	29.8729	0.53309	**0.4611**
1984 / 2015	21.8111	960.316	0.000515855	**0.0000**
2002 / 2015	29.8729	960.316	0.00096767	**0.0000**

Conclusively, there was a serious depletion in the mangrove coverage in four LGAs Epe, Eti-Osa, Ibeju-Lekki and Ikorodu. However, the depletion occurs in the rest of the LGAs around the Lagoon but not as clear as in the first four LGAs. From the year 2002 the rate of extinction of the mangrove (Figure 4.5) increased, and hence a steeply falling gradient (pronounced negative regression line) in the graph beginning from the year 2002 especially for Epe, Eti-Osa, Ibeju-Lekki and Ikorodu LGAs. This degree of change in mangrove to built-up area in all the LGAs around the Lagoon is evidence that the population is growing around the system. This has partly achieved part of the research objective number one, an investigation into the extent and impact of urbanisation on the Lagoon coastline. Changes in Lagoon ecosystem (among which is the mangrove) with a rising population density in the Lagoon coastline area will increase impervious surfaces and lead to diminishing capacity of the remaining wetlands to hold surface run-off. This will definitely endanger the quality of the Lagoon water. The investigation that reveals depletion in the mangroves has answered one of the research questions that say "is there spatial change around the Lagoon coastline and its ecosystem"?

4.5 Observed changes in the Swamps

The study area is rich in different wetland features, in addition to the investigation of changes in the mangroves of the study area, the spatial changes in the swamps coverage in each LGA in the entire study location was analysed from the results of the 1984, 2002 and 2015 images that were used in the research.

As the mangroves around the Lagoon were depleting rapidly, similarly the swamps were equally reducing constantly with time. The general results show that between 1984 and 2015, Apapa though has small area of swamps cover (Table 4.8), recorded the highest percentage decreased in swamp (Figure 4.9) which is about (95.65%) from $0.23km^2$ to $0.01km^2$ at the rate of $0.0071km^2$ per year deficit while Ikorodu LGA recorded the highest reduction in swamps area, the decrease was about 56% reduction from 98.1km^2 to 43.12km^2 at the rate of 1.77km^2 per year, followed by Eti-Osa LGA where depletion in swamps was by 83% from 38.69km^2 to 6.74km^2 at the rate of 1.03km^2. Results further shows that Epe, Ibeju-Lekki, Ikorodu, Eti-Osa and Kosofe in that order were the LGA with the largest area of swamps in 1984 with 132.22km^2; 124.39km^2; 98.1km^2; 38.69km^2 and 8.94km^2 respectively.

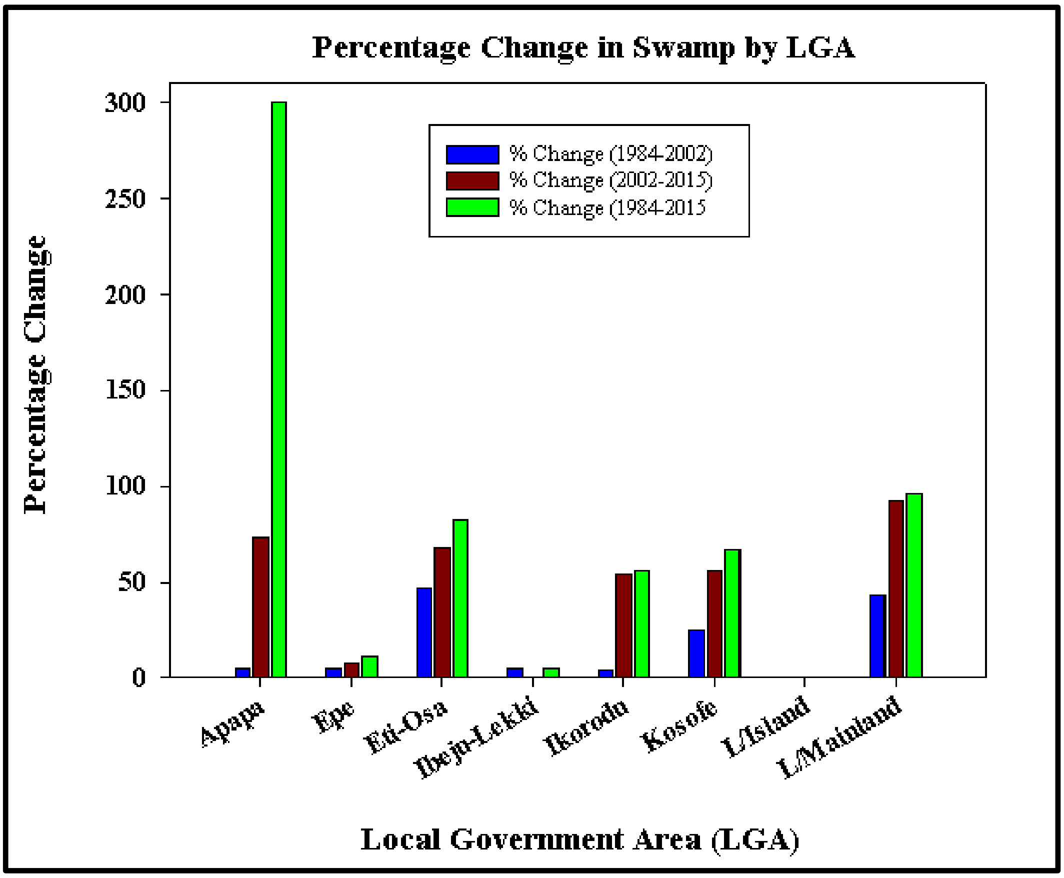


Figure 4.9: Percentage changes in Swamps by LGA around the Lagos Lagoon ecosystem from the year 1984 to 2015. Lagos Island has zero percentage change, an indication that the area is fully saturated in terms of urbanisation

Similarly, the swamps which had a sizeable presence in five local councils had reduced rapidly with almost half of their sizes (from about 402.77km^2 to about 287.59km^2) depleted in 2015. The relative loss of swamps and gains by replacing land cover mainly with built-up and bare land areas are displayed in Figure 4.11 and 4.12. A total of 115.18 km^2 of swamps has been lost to urbanisation between 1984 and 2015 at the rate of 3.71km^2 per year. If the swamp depletion trend is maintained at this rate, in about 70 years' time there will be no more swamps in any of the councils surrounding the Lagoon - that is a dangerous signal for the continued health of the Lagoon. This will make the Lagoon vulnerable to a huge threat biologically, chemically, morphologically and the consequence will also lead to changes in the natural balance of the Lagoon.

Table 4. 8: Coverage Area of Swamp by LGA from 1984 – 2015

LGA	1984 (km^2)	2002 (km^2)	2015 (km^2)	Change(km^2) (1984-2002)	Change(km^2) (2002-2015)	Change(km^2) (1984-2015)	% Change (1984-2002)	% Change (2002-2015)	% Change (1984-2015)
Apapa	0.20	0.19	0.05	-0.01	-0.14	-0.15	-5.00	-73.68	-75.00
Epe	132.22	126.10	116.83	-6.12	-9.27	-15.39	-4.632	-7.35	-11.64
Eti-Osa	38.69	20.74	6.74	-17.95	-14	-31.95	-46.39	-67.50	-82.60
Ibeju-Lekki	124.39	118.64	117.91	-5.75	-0.73	-6.48	-4.62	-0.62	-5.21
Ikorodu	98.10	94.21	43.12	-3.89	-51.09	-54.98	-3.97	-54.23	-56.04
Kosofe	8.94	6.72	2.93	-2.22	-3.79	-6.01	-24.83	-56.40	-67.23
Lagos Island	0	0	0	0	0	0	0	0	0
Lagos Mainland	0.23	0.13	0.01	-0.1	-0.12	-0.22	-43.48	-92.31	-95.65

*The negative signs on some of the figures indicate depletion in swamp

Comparative analysis of the observed variation in coverage area of mangroves and swamps between 1984 and 2015 (Figures 4.5 and 4.10) revealed that mangroves deplete faster than the swamps despite that the mangroves are closer to the Lagoon coastline than the swamps. It was only in Ikorodu local council that the gradient of depletion was very steep between 2002 and 2015; in other councils, the gradient is either very gentle or almost equal to zero, while Eti-Osa experienced constant linear depletion from 1984 - 2015. There is no doubt the Lagoon will be adversely impacted because of the fast disappearance in the mangroves and swamps which help in controlling erosion and flooding at the coastal plain.

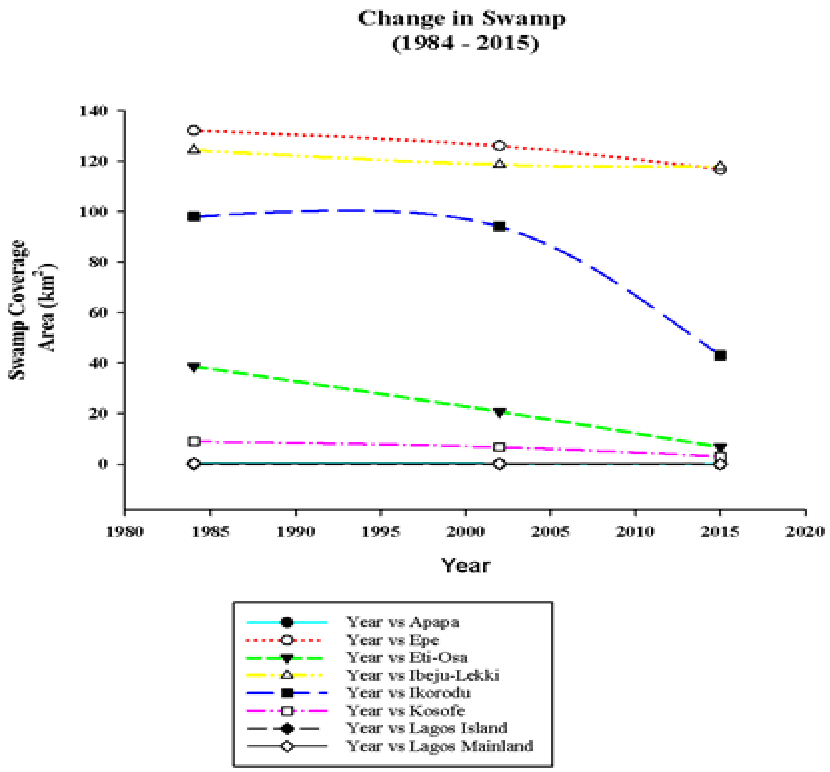


Figure 4.10: Graph depicting trend of changes in swamps by LGAs between 1984 and 2015

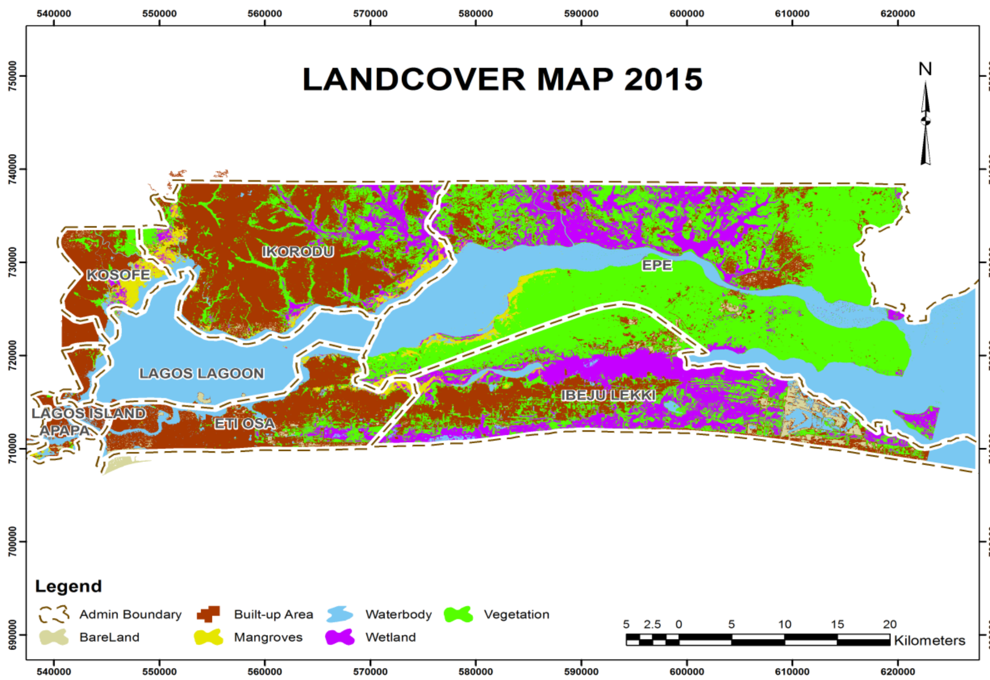


Figure 4.11: Map showing Land cover type around the Lagoon ecosystem by the year 2015 (Urbanisation seems to have reach saturation point because mangrove or swamp seem to be existing in the western region. It's just in few areas that little vegetation could be found)

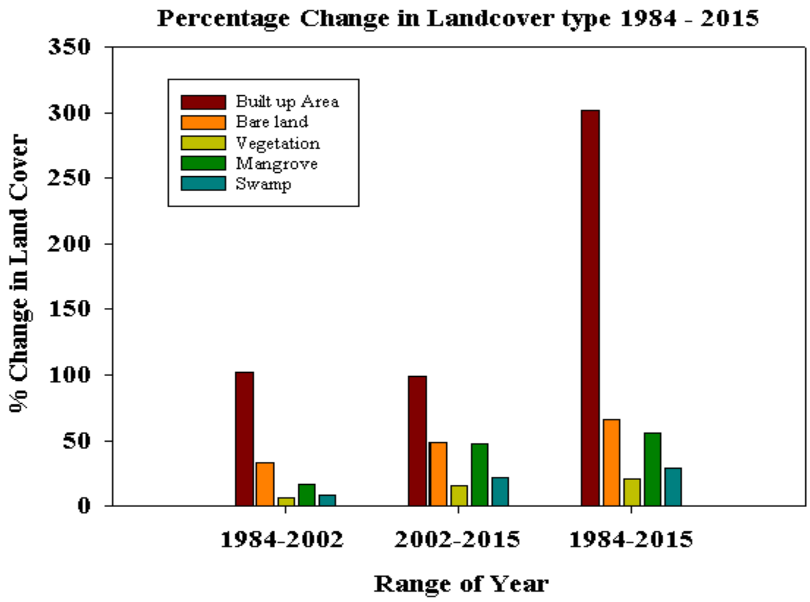


Figure 4.12: Percentage land cover changes on Lagos Lagoon ecosystem from 1984 – 2015. Among the Landover percentage shown in the Figure, only built-up percentage increased, others witness decrease. Built-up has the highest percentage (300%) between 1984 and 2015 almost six times the decrease in the mangrove area. So also is the swamp and vegetation decreased as the built-up area increases

4.5.1 Variability of swamps by local government area – ANOVA

Swamp as one of the strong indicators that the change that reveal changes in the Lagoon ecosystem was subjected to ANOVA test in order to test for the significance of the relationship that exists between year of study and the swamp coverage. The hypothesis used in section 4.4.1 holds for this section except that the variation this time is swamp variation instead of mangroves.

For the three series of years involved in the research data, the F-test indicates that $\boldsymbol{F_{cal}}$ is less than $\boldsymbol{F_{tab}}$ which is 0.63 at degree of freedom 2 and 22. Therefore, since the p-value is greater than 0.05 (0.5414), the null hypothesis is accepted. This indicates that there is no significant change between the mean changes from one series of years to another.

Table 4. 9: ANOVA Table for Changes by Series of Years

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	319.643	2	159.821	0.63	0.5414
Within groups	5051.83	20	252.592		
Total (Corr.)	5371.47	22			

Verdict on the hypothesis

A simple linear regression was performed on the changes in swamps for the three series of years to determine if there was a significant relationship between them. The F-statistics for the test was not significant (F-ratio = 1.32 and p-value 0.2636) at the 0.05 critical alpha level. Thus the null hypothesis is accepted, this does not mean that there may be no significant relationship between the variables (the changes in the swamps in relation to years). From the simple regression analysis, R^2 (Table 4.9), which is the coefficient of determination, shows the proportion of variability by providing a measure of prediction of swamp changes. This is also plotted in Figure 4.14. However, a further test was performed using Durbin-Watson (DW) statistics which assess the residuals to determine if there is any significant correlation based on the order in which they occur in the data file. The P-value from this test was less than 0.05 (0.0066) and Dublin-Watson statistics equals 0.9834. In conclusion there is an indication of serial correlation at the 95% confidence level (Figure 4.13). Hence there is significant relationship between the three series of years and the changes in the swamps coverage around the Lagoon. The simple linear prediction equation arrived at as a result of the test is shown in Figure 4.13 and the simple regression model.

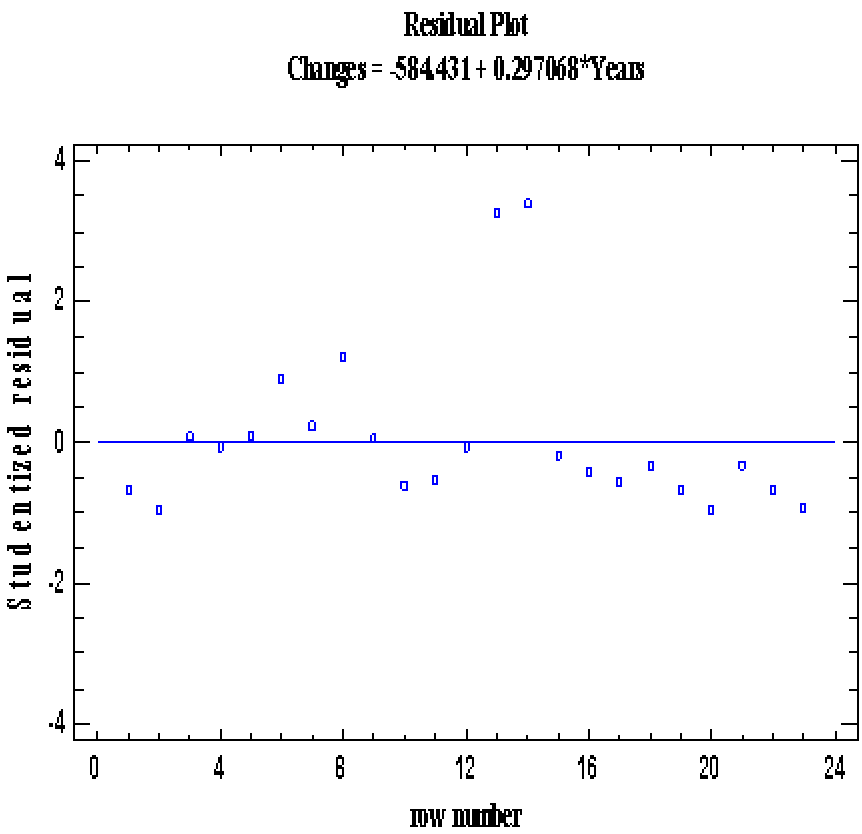


Figure 4.13: Plot of residuals versus row order

Table 4. 10: Correlation values between observed changes and predicted changes in swamps and their corresponding residuals

LGA by Year	Observed Change	Predicted Change	R	R^2
Apapa - 1984	0.01	4.41	-4.40	19.33
Apapa -2002	0.14	10.13	-9.99	2.94
Apapa - 2015	0.15	14.26	-14.11	183.44
Epe - 1984	6.12	4.41	1.71	1.81
Epe- 2002	9.27	10.13	-0.86	0.27
Epe -2015	15.39	14.26	1.13	4.78
Eti-Osa - 1984	17.95	4.41	13.54	19.41
Eti-Osa - 2002	14	10.13	3.87	18.54
Eti-Osa - 2015	31.95	14.26	17.69	99.76
Ibeju-Lekki -1984	5.75	4.41	1.34	0.74
Ibeju-Lekki - 2002	0.73	10.13	-9.40	14.99
Ibeju-Lekki - 2015	6.48	14.26	-7.78	88.33
Ikorodu - 1984	3.89	4.41	-0.52	1677.87
Ikorodu - 2002	51.09	10.13	40.96	40.17
Ikorodu – 2015	54.98	14.26	40.72	102.58
Kosofe - 1984	2.22	4.41	-2.19	100.16
Kosofe - 2002	3.79	10.13	-6.34	199.11
Kosofe – 2015	6.01	14.26	-8.25	1.28
Lagos Island - 1984	0	4.41	-4.41	312.91
Lagos Island - 2002	0	10.13	-10.13	60.54
Lagos Island – 2015	0	14.26	-14.26	1658.06
Lagos Mainland- 1984	0.1	4.41	-4.31	68.07
Lagos Mainland- 2002	0.12	10.13	-10.01	203.37
Lagos Mainland- 2015	0.22	14.26	-14.04	197.14

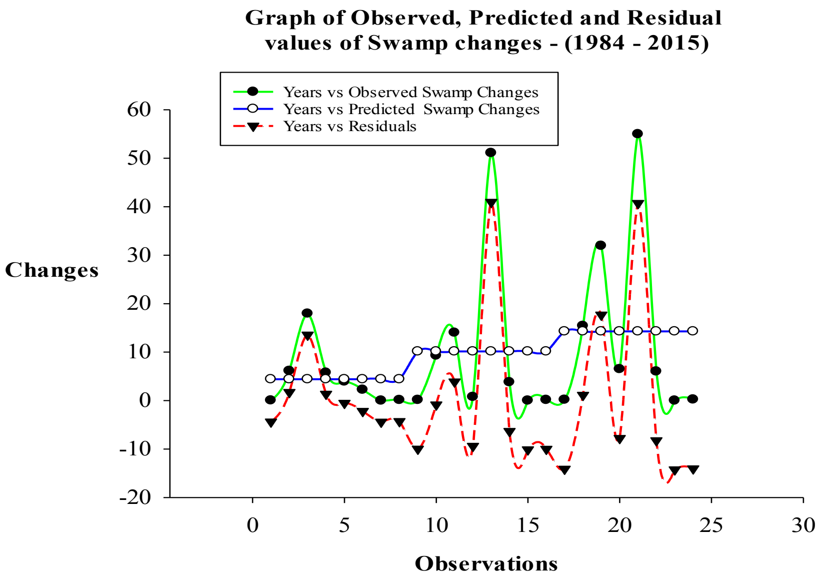


Figure 4.14: Graph of observed, predicted and residual values of swamp change in the LGA around the study Lagoon between 1984 and 2015

4.6 Observed changes in the Built-up and bare-land

Results in sections 4.4 and 4.6 show decrease in the coverage of mangroves and swamps respectively. In this section results show that the size of built-up area increased between 1984 and 2015. The built-up area increased by 301.79 percent (Tables 4.10, 4.11 and Figure 4.14) between 1984 to 2015 at a higher rate of 14.26km^2 per year. Results further show that the built-up area which were sparsely-spread in Eti-Osa, Ibeju-Lekki and Ikorodu LGAs in 1984 have increased widely with about 378.85km^2 within this LGA's with Ikorodu having the largest increase of about 192.72km^2. However, Ibeju-Lekki had the largest percentage increase of about 19722.76%. There is indication from the results that more population settlement is witnessed in Ibeju-Lekki council between the three series of years covered in the study.

Conversely, bare-land reduced by 78.61km^2 (65.97%) at loss rate of 2.54km^2 per year between 1984 and 2015. Furthermore, the results show that five local councils had the presence of sizeable bare-land in 1984 but by 2015 it had reduced down to cover only three local councils. More than half of the bare-land had been converted to built-up area. The relative loss of the bare bare-land and gain by the built-up areas are displayed in Figure 4.15.

Table 4. 11: Coverage Area of Built-up by LGA from 1984 - 2015

LGA	1984 (km^2)	2002 (km^2)	2015 (km^2)	Change(km^2) (1984-2002)	Change(km^2) (2002-2015)	Change(km^2) (1984-2015)	% Change (1984-2002)	% Change (2002-2015)	% Change (1984-2015)
Apapa	13.81	15.34	17.50	1.53	2.16	3.70	11.11	14.09	26.76
Epe	23.73	35.29	62.74	11.56	27.45	39.01	48.70	77.80	164.38
Eti-Osa	35.06	78.57	118.24	43.51	39.68	83.18	124.10	50.50	237.27
Ibeju-Lekki	0.52	51.47	103.44	50.94	51.98	102.92	9762.34	100.99	19722.76
Ikorodu	31.45	64.13	224.17	32.68	160.04	192.72	103.93	249.55	612.83
Kosofe	25.25	34.44	43.45	9.19	9.02	18.20	36.37	26.18	72.07
Lagos Island	5.13	5.18	5.35	0.05	0.17	0.22	0.95	3.35	4.33
Lagos Mainland	11.58	12.11	13.74	0.53	1.63	2.16	4.61	13.46	18.68
Total	146.53	296.52	588.65						

Table 4. 12: Estimation of land use classification of Lagos Lagoon ecosystem from 1984 - 2015

Land Cover	1984 (km^2)	2002 (km^2)	2015 (km^2)	Change(km^2) (1984-2002)	Change (km^2) (2002-2015)	Change (km^2) (1984-2015)	% Change (1984-2002)	% Change (2002-2015)	% Change (1984-2015)
Built Area	146.53	296.52	588.65	149.99	292.13	442.12	102.36	98.52	301.7229
Bare land	119.16	79.49	40.55	-39.67	-38.95	-78.61	-33.29	-48.99	-65.97
Vegetation	895.11	841.22	706.81	-53.90	-134.41	-188.31	-6.02	-15.98	-21.12
Mangrove	120.58	100.69	53.03	-19.90	-47.66	-67.55	-16.50	-47.33	-47.73
Swamp	402.66	366.83	287.60	-35.83	-79.23	-115.06	-8.90	-21.60	-28.57

- All figures with negative sign implies reduction in area or percentage

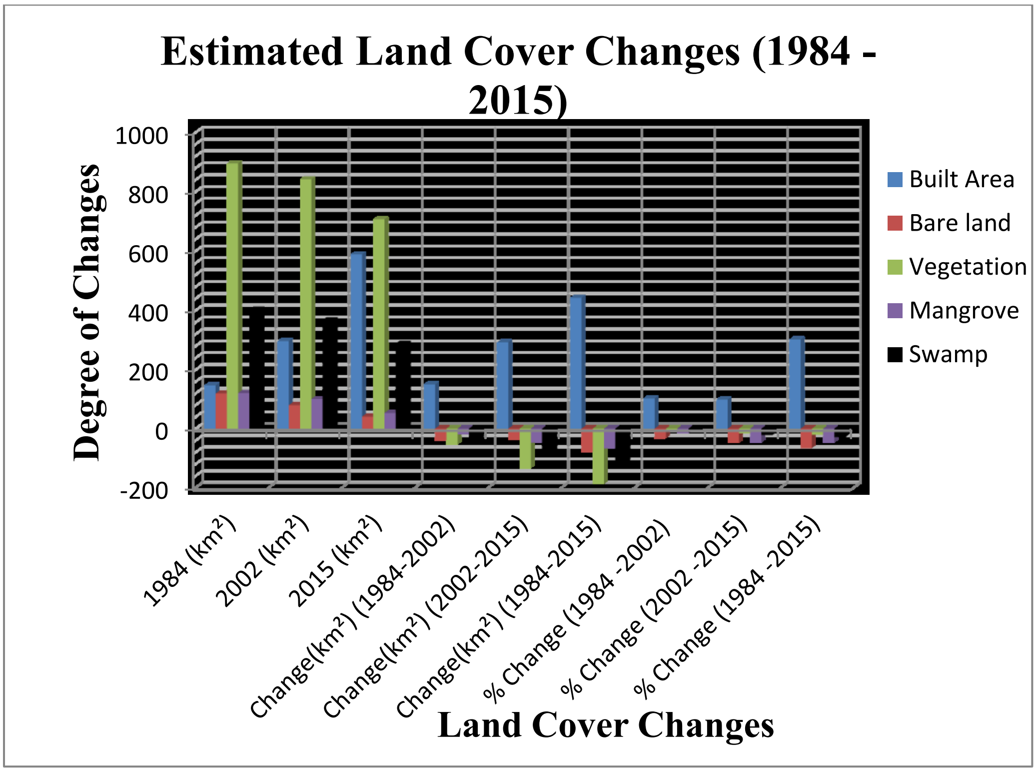


Figure 4.15: Extent of Land Cover Changes (1984 – 2015) in the Lagoon ecosystem, bars in the negative directions indicates depletion, while the bars in the positive direction imply increase. The chart shows (i) the extent of land cover in the three years of study, (ii) change between two years of study and (iii) percentage change

4.7 Land cover and Lagoon ecosystem changes associated with population growth

The results of sections 4.5 and 4.6 show the increases and decreases within land cover classification types that surround the studied Lagoon. As mangroves, swamps and bare-lands reduced in sizes between 1984 and 2015 built-up areas increased. This has also confirmed that there are more houses built between the years of study, hence increase in urban growth.

Based on Lagos State population statistics 1963, 1990 and 2006, the result in this section show that population and urban growth increase steadily together. This directly infringes on the quality and availability of mangroves, swamps, vegetation and bare-lands. Increases in human activities are a direct result of increased population and urban growth; these activities involve changes in the environment, sometimes expressed as a modification at landscape level. Almost any activity developed on a significant scale modifies the natural environment most at times in a negative way. Isn't this getting repetitive? Would you like to edit this down?

An Analysis of Variance (ANOVA) test was performed on the parameters (built-up, vegetation, swamps, mangroves and the bare-land) that were assumed to be experiencing changes against population in each LGA that surround the Lagoon. Hypothesis (Null and Alternate) were set thus:

- Null hypothesis (H_0): $\mu = 0$ (there is no significant difference in the mean of the land cover classification by LGA between 1984 and 2015).
- Alternate hypothesis (H1): $\mu \neq 0$ (there is significant variation in the mean of the land cover by LGA between 1984 and 2015).

The result of ANOVA test reveals an F-statistics of 20.63 and a p-value of 2.37E-10. Since the p-value is less than 0.01, the null hypothesis is rejected, therefore there is a significant difference among the mean values at 95% confidence level. Hence significant variations exist among the land cover types. However, Table 4.12 shows the degree of correlation that exists among the different land cover types as at the year 2015. The result from Table 4.13 shows that strong correlation existed between built-up area and mangroves, swamps, vegetation and bare-land with built-up versus vegetation having the strongest correlation. This corroborates the result of the depletion in section 4.4 and 4.5 that the reduction in mangroves, swamps, bare-land and vegetation correlates to increased built-up areas. Variables with linear relationship from the matrix plot (Figure 4.16) indicate a strong correlation with an increase or a decrease in one variable, leading to a decrease or increase in another variable (for example, built-up against mangroves).

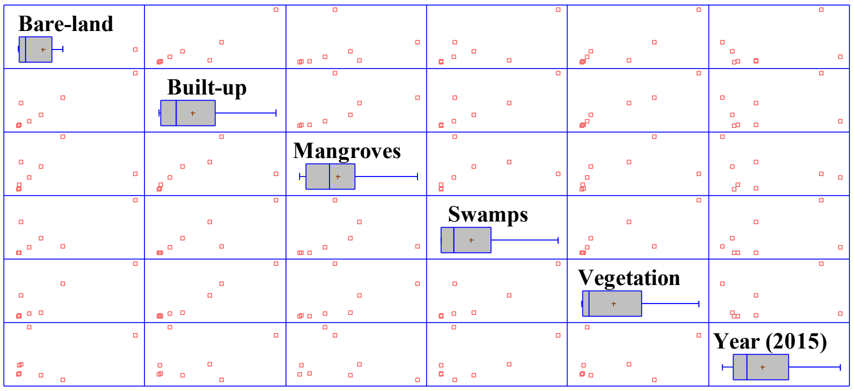


Figure 4.16: Matrix plot showing correlation among the variables: bare-land, built-up, mangroves, swamps, vegetation and 2015 population.

4.7.1 Environmental Variability within the study sites

While all the land cover classifications in the study site are considered "transitional ecosystems", suggesting an ephemeral and changeable nature, there are key differences between the changes in the built-up areas and the rest of the land cover classifications. In the case of built-up area around the lagoon, which is an effect that is generated from uncontrolled increase in urban development, the outcome leads to increasingly impervious surfaces contrasting with the swamps and mangrove ecosystems of the Lagoon. Therefore, with the exception of Lagos mainland and Lagos Island which had minimal coverage of mangrove and swamps, there is relatively high rate of transition of the wetlands (mangroves and swamps) around the Lagoon into settlement areas. This enables the creation of a new habitat structure with elimination of the initial natural ecosystem.

A consistent homogeneous increase in urban growth is witnessed from the western region of the Lagoon moving toward the east. The urban growth has witnessed saturation point in the LGA located at the western region of the lagoon while the three local councils that bounded the Lagoon by the east (Epe, Ibeju-Lekki and Ikorodu) are not as saturated as Apapa, Lagos Island, Lagos Mainland and Kosofe. The trajectory of the urban development in the ecosystem of the Lagoon can be traced eastward from the west end of the Lagoon. A certain amount of heterogeneity of change is witnessed around the Lagoon coastline due to the variability in increased human activities; this is supported by the result of Obiefuna *et al.* (2012). A good example is discussed as part of the results in chapter five about the variability in sediment flux around Ogudu channel which may be due in part to the conversion of the natural wetlands to settlement area.

Clearcutting urbanisation and land use without development plans has resulted in landscape fragmentation and change of natural morphology of the Lagoon coastline. This will have contributed significantly to the decline and loss of coastal wildlife populations. A good example is the wetland ecosystem of the University of Lagos and Abule-Oja in Lagos mainland LGA, where colonies of monkeys, crabs and other associated marine habitats are living. As more swamp around the community is converted to impervious surface and built-up areas, the wetland habitat has greatly reduced. Interestingly, the monkeys and crabs that have very large population in the ecosystem are hardly in existence in the small portion of the swamp left in the area (Abere & Ekeke, 2011; Daramola & Ibem, 2010). Isebor (2004) corroborated the above statement by stressing that the Nigerian coastal mammals dwells in unfriendly terrain due to the fact that marine environment continues to come under serious risk generally associated to development pressure, this impede the soundness of the marine environment and negatively impact the biodiversity.

Table 4.13: Correlation relationship of the various land use type in the study site as at the year 2015 (built-up against swamps and mangroves, bare-land against vegetation show the strongest correlations. This suggests that a slight change in one of the variables leads to a corresponding visible change in the other)

	Year (2015)	Swamps	Vegetation	Mangroves	Built-up	Bare-land
Year (2015)	1					
Swamps	0.46	1				
Vegetation	0.29	0.82**	1			
Mangroves	-0.24	0.23	0.55*	1		
Built-up	0.33	0.89**	0.99**	0.52*	1	
Bare-land	0.42	0.79**	0.90**	0.31	0.91**	1

** Strong correlation; * Average correlation

4.8 Population Growth and Depletion in the Lagoon Ecosystem's Wetland

The population data for Lagos State only covers the years 1963, 1990 and 2006. Because of the need for population data that covers the period (1984, 2002 and 2015) of investigation in this section, a linear regression analysis was carried out on the data which generate the regression Equation 4.1 and the linear graph (Figure 4.17). The analysis of the regression revealed an R^2 value as 1, this ascertain that any population prediction from the regression equation will give a relatively close value to the actual population value of that year.

$$f(x) = p_1x^2 + p_2x + p_3 \qquad 4.1$$

Where $f(x)$ = population

x = Year, p_1 = 1697, p_2 = - 6558000, p_3 = 6335000000

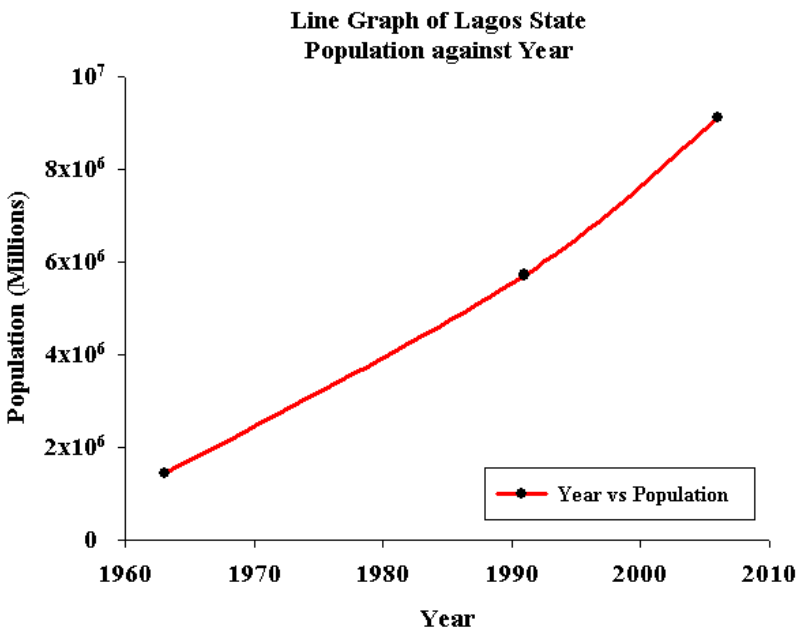


Figure 4.17: Population trend around the Lagos Lagoon ecosystem using the available population data from National Population Commission of Nigeria.

From Equation 4.1, predicted population figures for 1984, 2002 and 2015 were computed as shown in Table 4.13. The actual and predicted population figures for 1963, 1991, 2006, 1984, 2002 and 2015 respectively were used to plot the population trend in Lagos between 1963 to 2015 (Figure 4.18). The predicted population figures were used with the total area of each of the land cover changes to carry out linear regression analysis in order to verify the relationship between the years, the wetlands (mangroves, swamps and vegetation) and urban development (built-up).

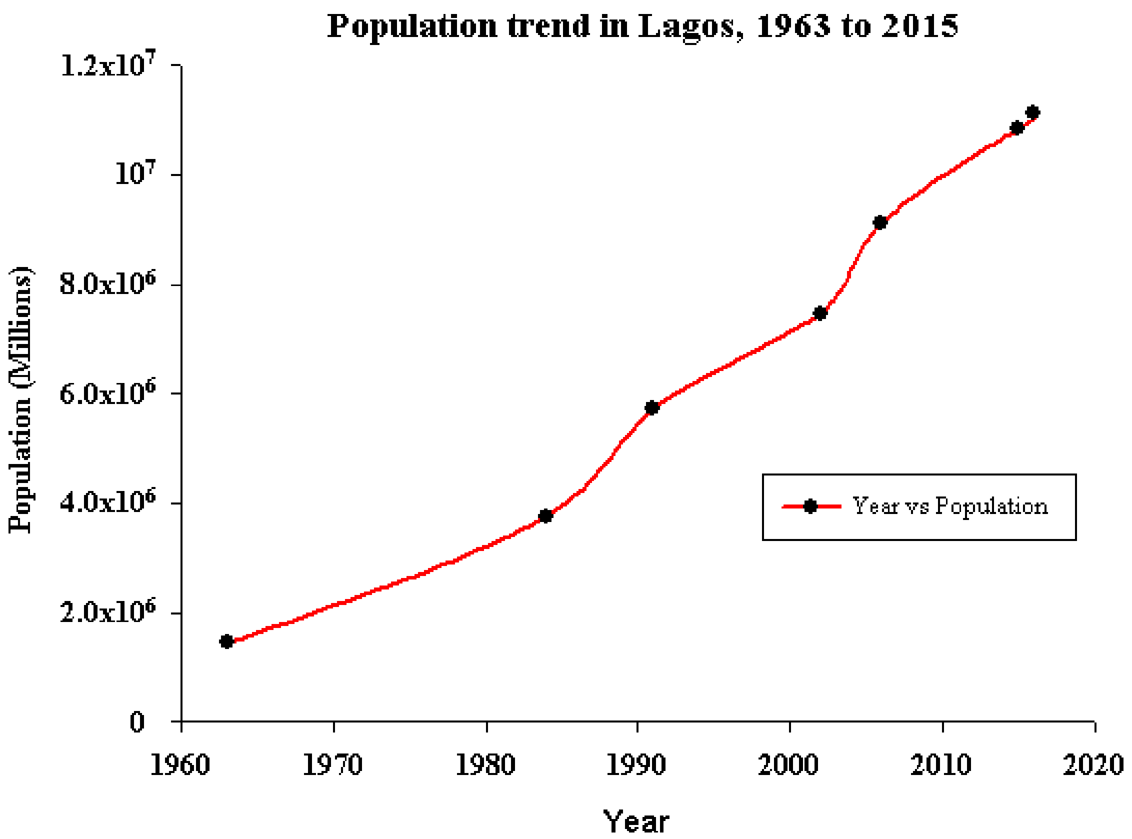


Figure 4.18: Trend of Lagos State population using the actual population figure and computed population data.

Table 4.14: Population figure of Lagos State, with actual population figure in bold print, the actual figures were used to compute the predicted values in bold italic

Year	Acquired Population (Millions)	Predicted Population (Millions)
1963	**1443569**	**-**
1984	**-**	***3754432***
1991	**5725116**	**-**
2002	**-**	***7466788***
2006	**9113605**	**-**
2015	**-**	***10831825***
2016	**-**	***11114432***

*Source: National Population Commission of Nigeria, 2006

4.8.1 Linear regression analysis of built-up, vegetation, swamps and vegetation

Linear regression analysis was applied to the area covered by wetlands and the built-up around the Lagoon ecosystem based on the period covered in the study. The significance level was set as $\alpha = 0.05$ and all the relationships with significant impact for each variable compared are shown in bold print in Table 4.14. Figures 4.19 and 4.20 summarise these results. As the rate of built-up increased, the area of wetland coverage decreased steadily. Alternatively, the built-up area increased with population; however, the various wetlands decline with increased population.

Table 4.15: Computed values of R^2 and p-value with their corresponding correlation relationship between groups

Variable group	R^2	P-value	Correlation (positive or negative)
Population v Mangrove	0.904	0.200	Negative
Population v Swamp	0.908	0.196	Negative
Population v Vegetation	0.892	0.213	Negative
Population v Built-up	0.926	0.176	Positive
Built-up v Mangrove	0.999	0.024	Negative
Built-up v Swamp	0.999	0.0197	Negative
Built-up v Vegetation	0.997	0.037	Negative

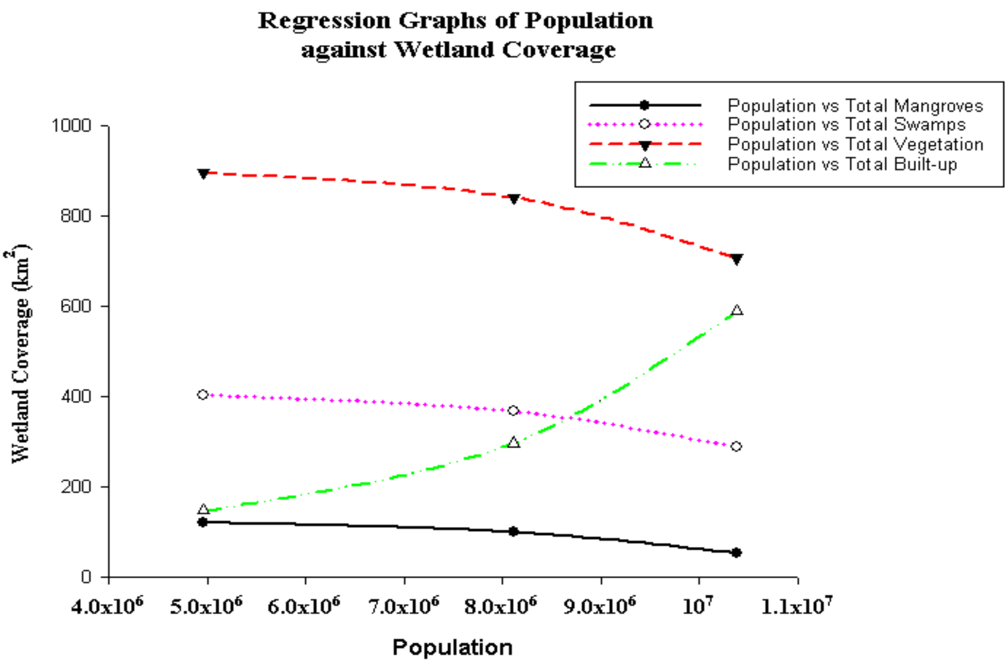


Figure 4.19: Regression graph showing correlation relationship of population against mangroves, swamps, vegetation and built-up areas.

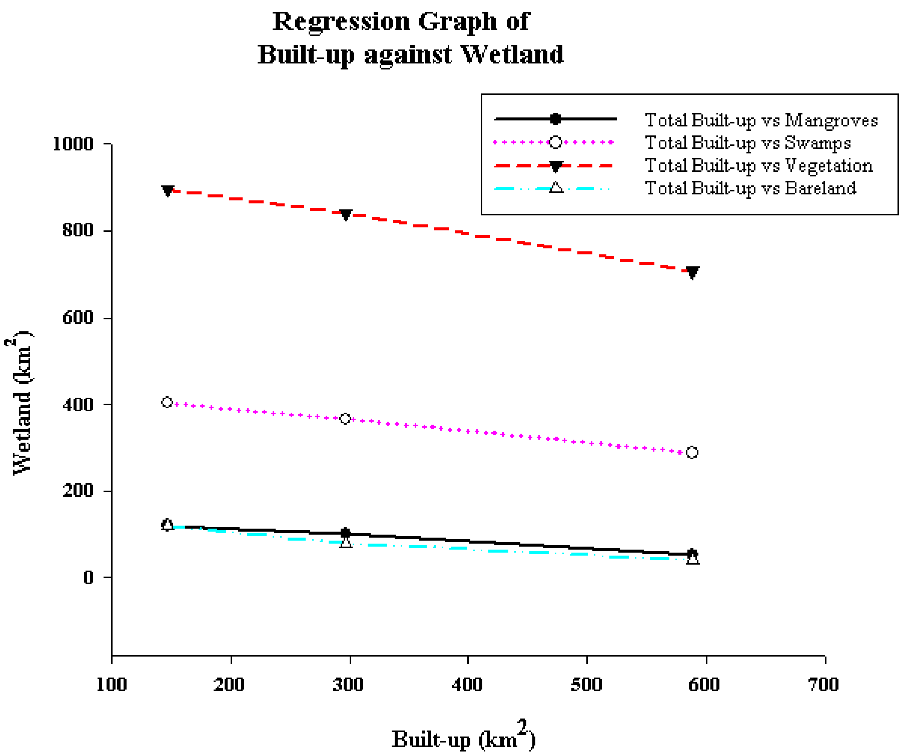


Figure 4.20: Regression graph showing correlation relationship of built-up area against mangroves, swamps, vegetation and bare-land

From Table 4.15, a negative correlation was found to exist for six out of the seven variable groups that were compared and one positive correlation between the built-up area and population. However, the p-values for the groups built-up versus mangrove, built-up versus swamp and built-up versus vegetation indicate statistically significant relationships between each of the groups whereas the p-values of other groups from the Table do not indicate statistically significant relationships. Although, the p-value for built-up versus population group was greater than 0.05, indicating no significant relationship notwithstanding the graph in Figure 4.18 signifies that a significant positive relationship exist between the built-up versus population growth. The positive correlation of the two variables (built-up and population) is the basis of Waycott *et al.* (2009) reasoning that coastal ecosystem are negatively impacted by human population and the variety of their activities.

In summary, as the population increases, so the built-up area increases. In contrast, the mangroves, swamps, vegetation and bare-land tend to deplete. This indicates that urban development in Lagos encroaches on the wetlands around the Lagos Lagoon causing their fast depletion.

4.8.2 Regression analysis of Wetlands by LGAs

Further regression analysis was carried out using the population of the local councils surrounding the Lagoon with the combination of wetland depletion and increasing urban development (built-up) within the Lagoon ecosystem. From the population data of 1963, 1991 and 2006 collected from National Population Census, the population figures for the eight local councils surrounding the Lagoon were extracted. Regression analysis was performed on the extracted population dataset, the curve of its graph (Figure 4.21) fits into polynomial of second order shown in Equation 4.2.

$$f(x) = p_1x^2 + p_2x + p_3 \qquad - 4.2$$

From the polynomial fit Equation, the population figure for 1984, 2002 and 2015 were computed as in Table 4.15. R^2 value of 1 was obtained for the fitted polynomial regression; this indicates that the equation is suitable for predicting population figure for any of the years where there is no population data. Table 4.15 and Figure 4.21 summarise the population results with the predicted population recorded in italic bold print on the table.

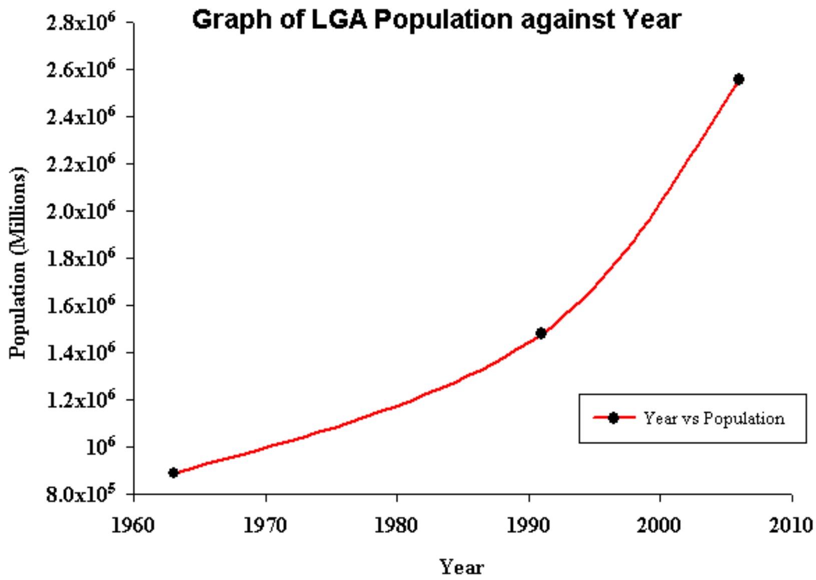


Figure 4.21: Regression graph showing trend of population increase in the eight local councils surrounding the Lagoon ecosystem. The trend fit into polynomial of second order

Table 4.16: Population figure of the 8 Local Government Councils surrounding the Lagoon Acquired population fires are in bold print while predicted population figures are in bold italic print)

Year	**Acquired Population (Millions)**	**Predicted Population (Millions)**
1963	890595	-
1984	-	*1101568*
1991	1480462	-
2002	-	*2154712*
2006	2556393	-
2015	-	*3390050*

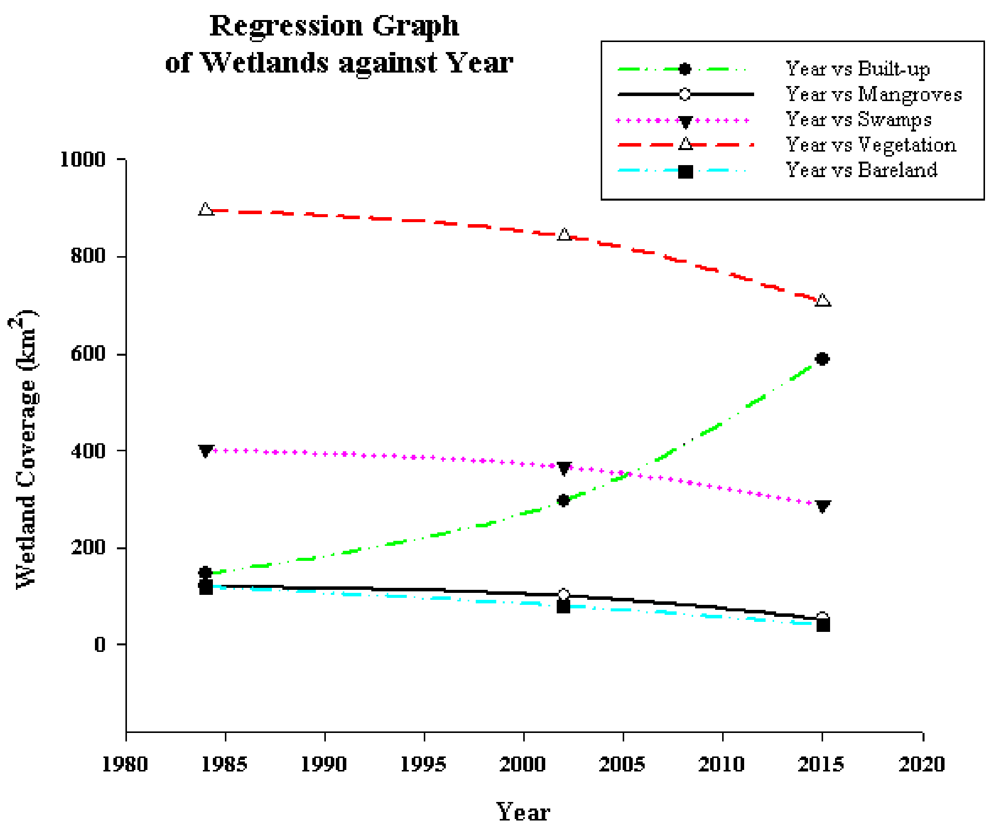


Figure 4.22: Regression analysis showing correlation relationship of the population of the 8 LGA surrounding the lagoon wetlands and built-up areas.

Figure 4.22 reveals that four of the regression analysis results have negative correlation (the swamps, mangroves, vegetation and bare-land) while the result of the built-up shows positive correlation. Between 2002 and 2015 the rate of built up in the eight local councils increased spontaneously (Figure 4.22); however vegetation and swamp areas decreased in a direct proportion to the increase rate of the built up area. These can be interpreted and summarised that as the population of the local councils surrounding the Lagoon increased, the wetlands diminished but conversely built-up area increases. The rapid depletion in the Lagoon ecosystem wetlands can be attributed to the rapid increase in urbanisation that has been witnessed by Lagos state. The population of the eight local councils within the Lagoon ecosystem has more than doubled from approximately 1.4 million in 1990 to 3.4 million in 2015. This has led to increased urbanisation and attributed to the reason for the reduction of natural wetlands in the Lagoon ecosystem, replacing them with built-up and other materials with capacities to retain heat and thereby causing serious environmental stress that affects the urban micro-climate. With this huge depletion and replacement of the wetland with urbanisation, there is need to monitor the rate at which Land Surface Temperature (LST) increases in the study area with the land use dynamic.

4.9 Results of Landsat images by colour based segmentation from Matlab

The process in this section with the use of enhancement of colour separation and *K-means* cluster has been able to harmonise homogeneous regions in the Landsat images used and then do a classification of the different regions. Thus the cluster images of the Landsat series show the status of urbanisation in the Lagoon ecosystem. Continuous evaluation of the cluster images from year to year, especially if this could be done every year or every two years, can give accurate status of the development going on in any particular area of the lagoon ecosystem. The result of the colour based segmentation in this section has been able to identify areas where there is disappearance in some set of classification and an increase in another type of classification. Although the results of the classification type from the Matlab program does not maintain constant colour from one particular year to another, yet the different results with the colour pigment were able to show distinct spatial variability in the land use classification as it occurred from one particular year to another.

Figures 4.23 to 4.26 show the results of the segmentation of four different Landsat images using *K-means* clustering method with four cluster classifications. The method has the main advantage of finding a local optimum for any existing centroid locations (Malinen *et al.,* 2014). The results in Figures 4.23 to 4.26 exhibits the same pattern of changes as recorded in sections 4.4 to 4.7, a direct proportionate relationship. As the surface area of urban settlement increases from the western region of the Lagoon towards the east, wetlands (mangroves, swamps and vegetation) decreased or disappeared.

Comparing the results of 1990, 2002 and 2015, the small collection of waterbodies in Figures 4.23, 4.24 and 4.25 (represented with light blue in 2015, 2002 results and red colour in 1990 result) were very visible in 1990 in some portions within the ecosystem moving west to east in the Lagoon ecosystem. However, the statement of Dutta (2012) that land use dynamic is a basic factor that influence urban growth support the finding by the year 2015 where almost all the areas with collections of small waterbodies in previous years have been converted to urban settlements in the western region of the ecosystem,. Furthermore, the built-up area is increasing from the west to the east comparing the three results. This suggests that built-up area has increased greatly over fifteen years. Moreover, comparing the colour pigment representing the built-up and bare-land in 1990 and that of 2015, it could be visually judged that these segments have expanded in 2015. Conversely, the wetlands and waterbodies within the settlement area are disappearing. The result in this section agreed with what was achieved is section 4.4 to 4.7 even though different methods were used in achieving them.

The results suggest that the use of *K-means* method for classification and segmentation in Landsat images is robust because it accurately segments the various land uses of the Lagoon ecosystem with different distinct colour separations. Interestingly, one of the inferences from section 4.4 to 4.7 that the land cover classifications in the lagoon ecosystem are considered “transitional ecosystem” can be verified and ascertained by the results from this model. As the areas covered by built-up and bare-land are increasing over the years, the surface area of vegetation (mangroves, swamps and vegetation) is depleting.

With the introduction of this model, it has been possible to monitor the growth of urban development and the influence it induced on the swamps, mangroves and vegetation. Hence, this model has successful fulfilled part of the objective four of the research.

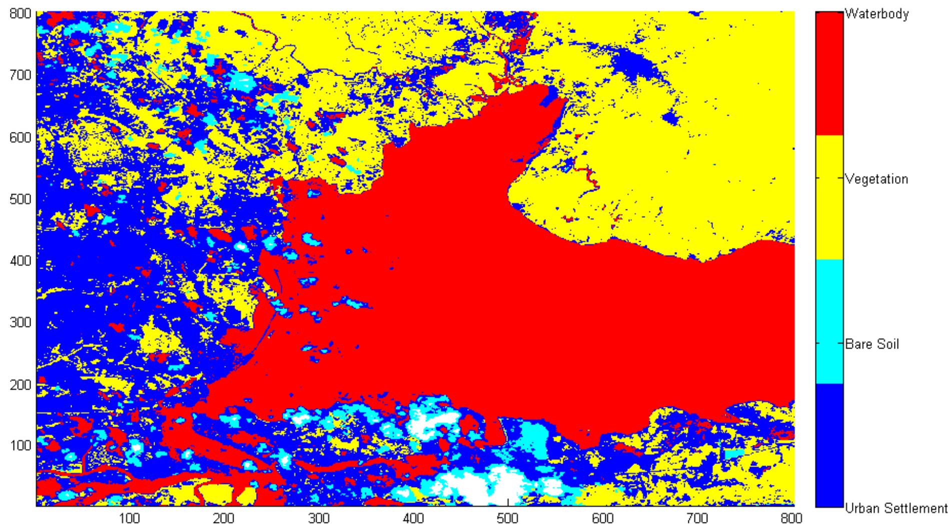


Figure 4.23: Result of land cover type generated from Landsat image of 1990

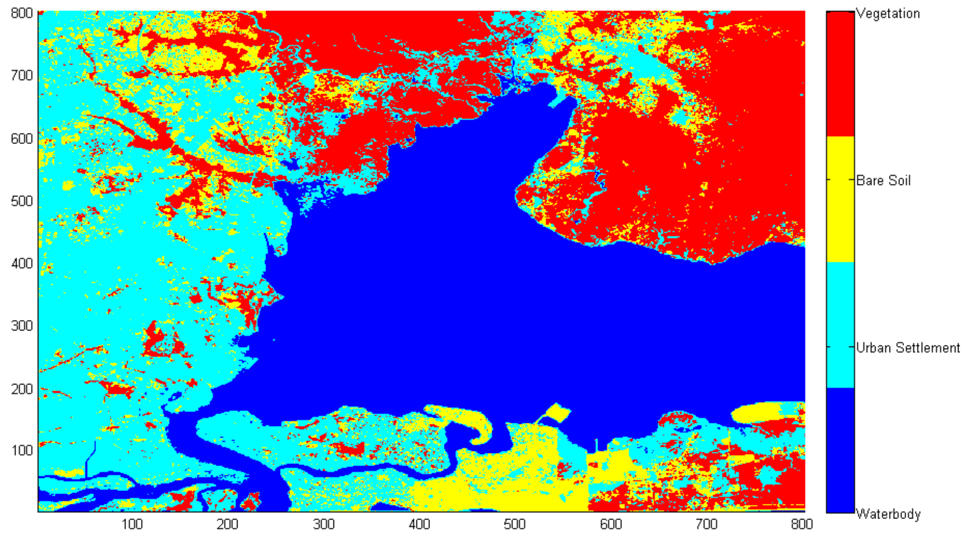


Figure 4.24: Result of land cover type generated from Landsat image of 2002

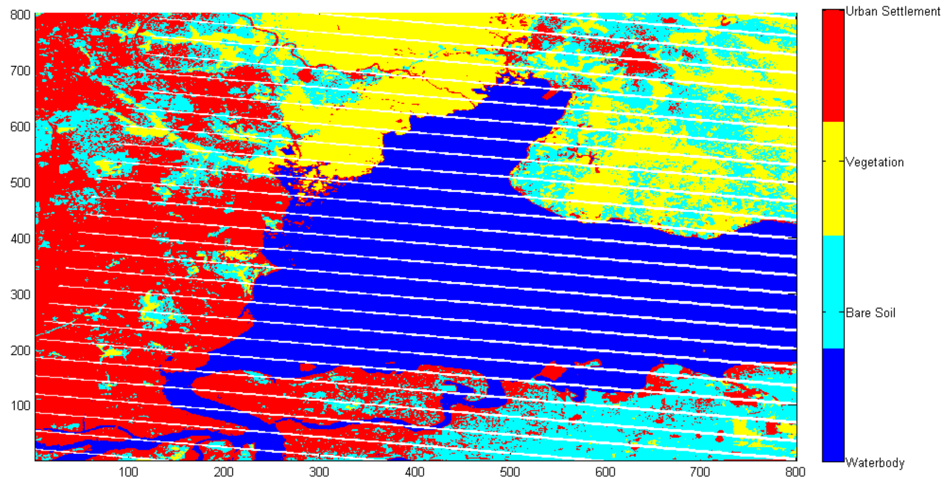


Figure 4.25: Result of land cover type generated from Landsat image of 2014

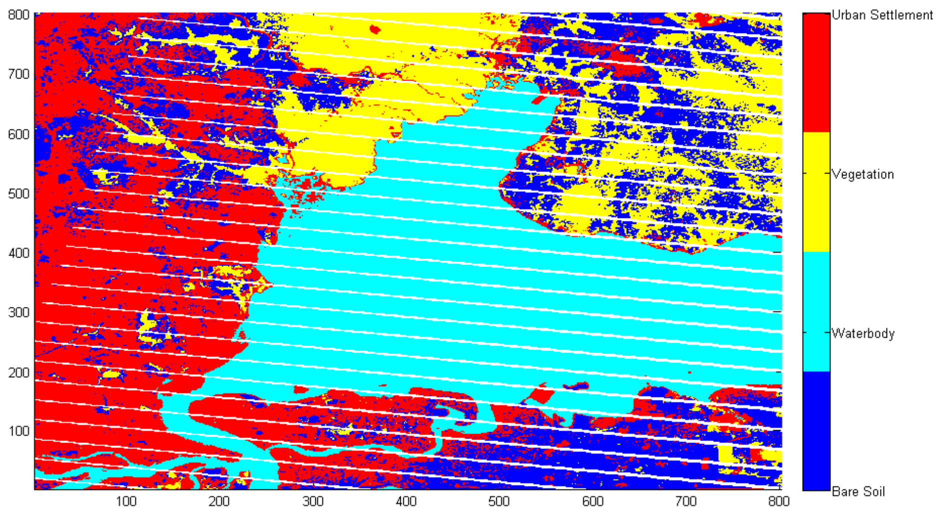


Figure 4.26: Result of land cover type generated from Landsat image of 2015.

4.9.1 Model Result of Land Surface temperature (LST)

In addition to the land cover classification derived from the model in this section, Land Surface Temperature (LST) of the area was generated using the developed Matlab model in this section. The results of the generated LST from Landsat images 1990, 2002 and 2015 were plotted in Matlab environment as depicted in Figures 4.27 – 4.29. Comparing the three trend plots, it could be observed that the entire southern region of the Lagoon ecosystem has absolutely high LST for the three Figures moving from west to east. Even though there was rapid urbanization within the Lagoon ecosystem, it seems this did not create a high rate of change in LST of the area. The mean of the LST estimated from the model study shows that the land surface temperature in the study area only increases slightly with increasing rate of urbanisation. Table 4.16 shows the summary of the mean LST for the interval of twenty five years covered by this section of the study. It can be observed that LST increased slowly from approximately 306 Kelvin to 308 Kelvin (33°C to 35°C).

Notwithstanding, there was visible spatial variability in the distribution of the LST from 1990, to 2015. It could be observed from Figures 4.27 to 4.29 that in 1990, there was a gap of low LST at the northern region of the ecosystem which implies that urban growth was very low at this area. However in 2002 and 2015, the LST of the area has gradually increased leaving behind a smaller region with low LST. It could be noted that the region of low urbanisation pointed out in Figure 4.27 with low LST has gradually changed in the results of 2002 and 2015. The average LST value in the area has increased from approximately 298 Kelvin (25°C) in 1990 to approximately 304 Kelvin in 2015. According to Table 4.15, the population of the eight local councils within the ecosystem increased from approximately 1.4 million in 1990 to 3.4 million in 2015; this shows that the land surface temperature (LST) is increasing with the urban growth.

Table 4.17: Average LST of the Lagoon ecosystem

Year	Mean LST (Kelvin)
1990	306.49
2002	307.06
2015	308.04

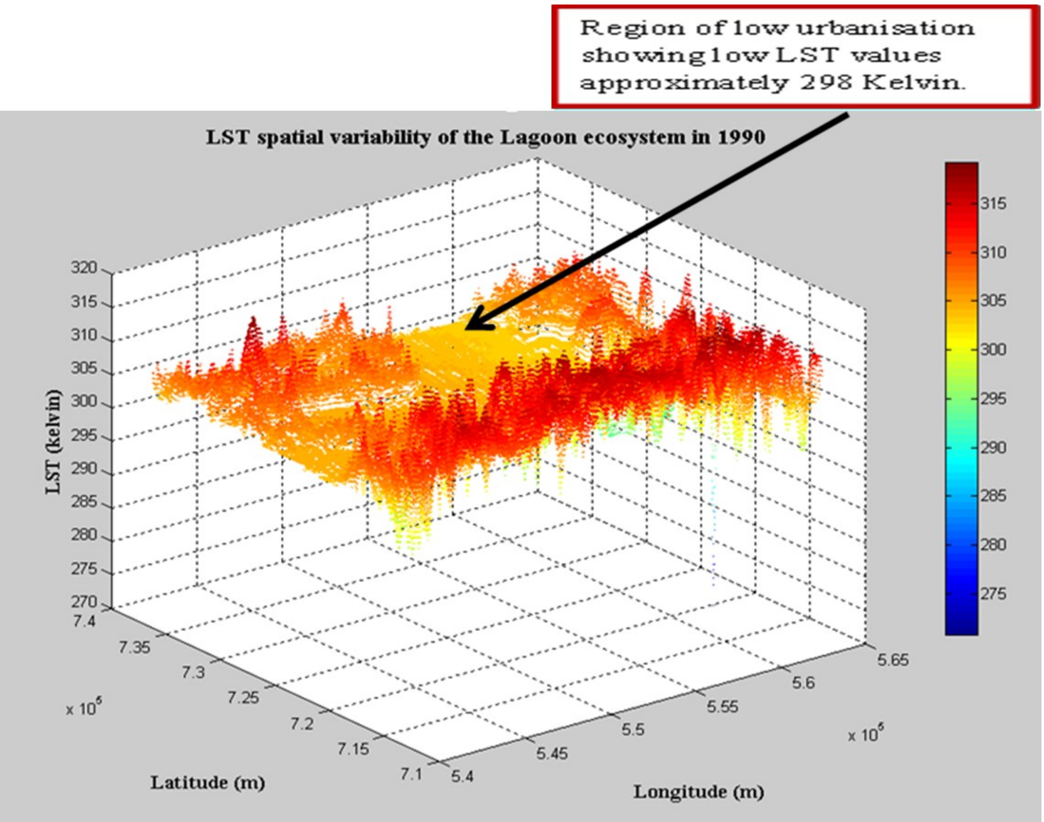


Figure 4.27: Trend of LST generated from 1990 Landsat image, the range of LST was averagely 295 – 314 Kelvin

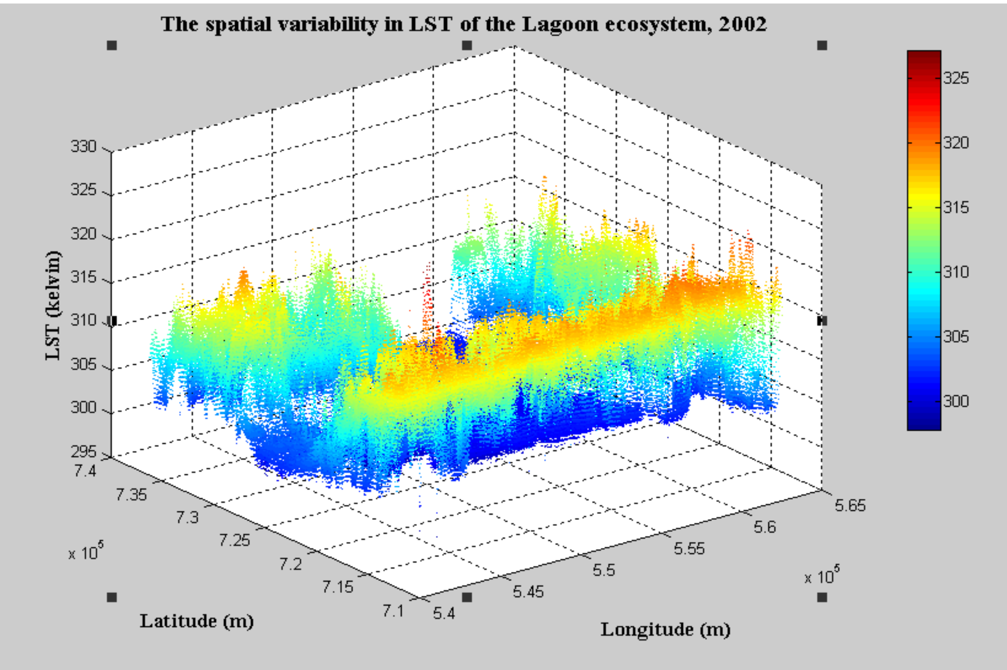


Figure 4.28: Trend of LST generated from 2002 Landsat image, the range of LST was averagely 301 – 315 Kelvin

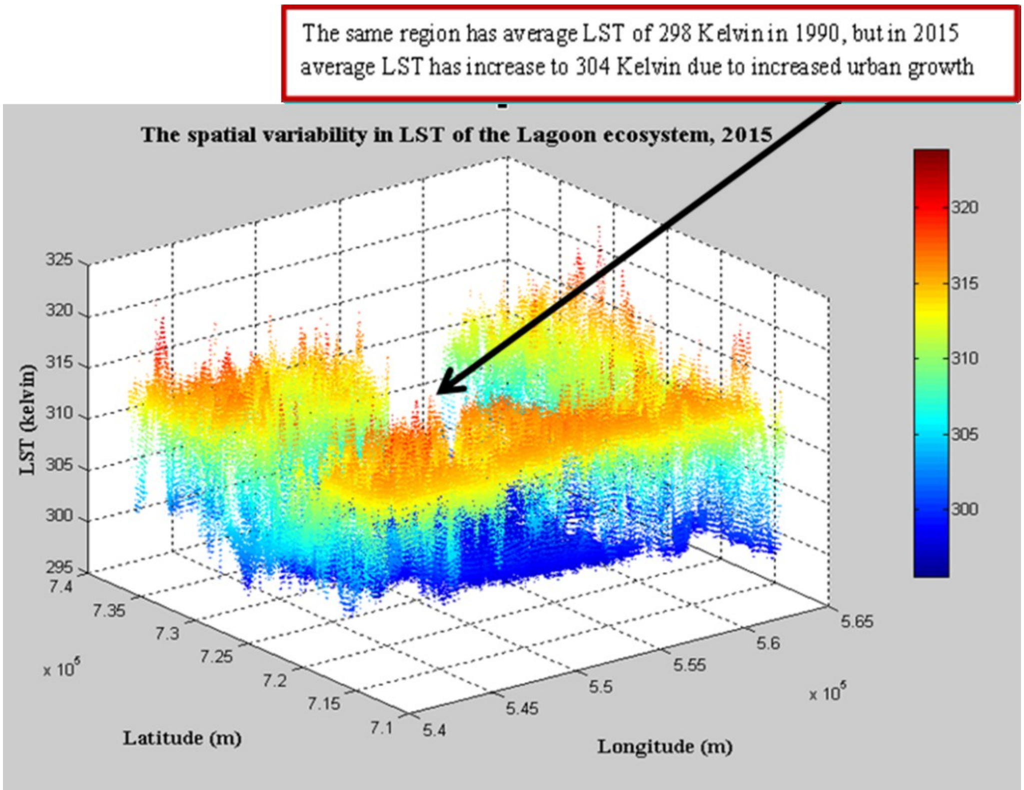


Figure 4.29: Trend of LST generated from 2015 Landsat image, the range of LST was averagely 297 – 320 Kelvin

4.9.2 Significance of the ecosystem LST spatial variability

To make it possible to identify the spatial variability in the lagoon ecosystem LST, a new variable, change in LST (ΔLST) was defined for the LST at the north, west and south. The ΔLST is the difference between the LST of a particular location where development begins at the most western region of the ecosystem and LST values of different locations as we move eastward. For the western LST (LST_W), since development begins from south to north, ΔLST is computed as the difference in the LST of a point down-south of the west where development stars from and the LST values of locations northward. To establish the reliability on the LST as a true measure of urban growth, analysis of variance (ANOVA) was performed to test whether as we move away from the western region where there is high rate of development, if there were statistical significant difference at 0.05 confidence level.

The ANOVA analysis procedure for change in LST compared data in three columns as ΔLST_N, ΔLST_S, and ΔLST_W. It constructs various statistics tests to compare the dataset, among which are: F-Test in the ANOVA table test (Table 4.18) whether there is any significant difference among the means. Table 4.18 gives the summary of the F-ratio and the p-values that show whether there is any significant difference in the mean of the change in LST in each of the year covered in the study. Homogeneity of variances always stipulates an assumption that in any statistics analysis, the variances of the different dataset to be tested are similar. This test was carried out on the various groups for each year using Levene's test. The results of the test (Table 4.18) show p-values that indicate whether the variances of the dataset in each group were significantly different or not. Comparing the p-value from ANOVA and Levene's test, it was evident that there is statistically significant difference in the LST spatial variation on the ecosystem.

Table 4.18: ANOVA and Levene Test Table for testing the variance in the mean of ΔLST

Group data set	**Year**	**F-Ratio**	**P-value**	**P-value from Levene's Test**
ΔLST_N, ΔLST_S and ΔLST_W	1990	24.34	0.0000	0.000407191
ΔLST_N, ΔLST_S and ΔLST_W	2002	22.79	0.0000	0.000113092
ΔLST_N, ΔLST_S and ΔLST_W	2015	20.74	0.0000	0.00000000

To determine which means are significantly different from the others, Multiple Range Test was performed using Fisher's least significant difference (LSD) procedure. Summary of the p-values of all the group data used with number of significant results from the Multiple Range Test are tabulated in Table 4.19.

Table 4.19: Multiple Range Tests, which reveals which means are significantly different from the others

Group	Year	F-Ratio	P-value	R^2	Correlation	Significance
ΔLST_N - ΔLST_S	1990	0.219223	0.0002	-0.2726	Negative	*
ΔLST_N - ΔLST_W	1990	0.71034	0.3979	0.0471	Positive	
ΔLST_S - ΔLST_W	1990	3.24026	0.0053	0.2465	Negative	*
ΔLST_N - ΔLST_S	2002	2.55496	0.0123	0.0477	Negative	*
ΔLST_N - ΔLST_W	2002	1.11497	0.7876	0.2062	Positive	
ΔLST_S - ΔLST_W	2002	0.436392	0.0312	0.0098	Negative	*
ΔLST_N - ΔLST_S	2015	11.1106	0.0000	0.1396	Negative	*
ΔLST_N - ΔLST_W	2015	1.9024	0.0637	0.1029	Positive	
ΔLST_S - ΔLST_W	2015	0.171223	0.0000	0.0173	Negative	*

*denotes a statistically significant difference

From Table 4.19, the results show that all the groups' ΔLST_N - ΔLST_S and ΔLST_S - ΔLST_W were negatively correlated while positive correlation were achieved for ΔLST_N - ΔLST_W. This implies that for period considered in the study, LST decreases both at the western and northern region of the ecosystem moving from west to east and south to north directions respectively. However, the p-values for both ΔLST_N - ΔLST_S and ΔLST_S - ΔLST_W do indicate statistically significant change.

An investigation was also made on how LST along the Lagoon coastline varies by carrying out analysis on the LST values along the Lagoon coastline during the period of the study (1990, 2002 and 2015). The statistical analysis tests the null hypothesis that the standard deviations within each three column datasets are the same. Of particular interest is the p-value displayed in Table 4.20; it also shows a comparison of the standard deviations for each pair of samples. Two of the groups compared show a p-value below

0.05; this implies a statistically significant difference between the two standard deviations (σ) at 95% significance level.

Table 4.20: Comparison test of null hypothesis that the standard deviations within each compared groups are the same

Comparison	σ_1	σ_2	F-Ratio	P-Value	Significance
LST1990 v LST2002	3.93886	6.2755	0.393953	**0.0023**	Yes
LST1990 v LST2015	3.93886	6.70626	0.344968	**0.0005**	Yes
LST2002 v LST2015	6.2755	6.70626	0.875659	0.6580	No

It could be inferred from Table 4.19 that there was significant change in the LST values (p-values of 0.0023 and 0.0005) along the Lagoon coastline from 1990 to 2002 and between 1990 and 2015; this change goes along with the variation detected from the depletion in the Lagoon wetlands which was discussed in sections 4.8.1 and 4.8.2. Obviously, the urban expansion in Lagos has impacted changes along the Lagos Lagoon coastline. Without doubt, the natural coastline of the lagoon must have been altered as a result of struggle for space for settlement which must have invariably caused part of its immediate coastline boundary to be encroached upon for building purposes.

4.10 Spatial distribution of LST - NDVI correlation over the Lagoon ecosystem

A large number of water and climate related applications, such as spatial drought monitoring, are based on space borne derived relationships between land surface temperature (LST) and the normalised difference vegetation index (NDVI) (Karnieli *et al.,* 2010; Pettorelli *et al.,* 2005). The majority of these applications rely on the existence of a negative slope (Wilson *et al.,* 2003; Yue *et al.,* 2007) between the two variables, LST and NDVI, as identified in study location and time specifically.

The results of the investigation in this section show the generality of the LST-NDVI relationship of climatic/radiation regime encountered over the Lagos Lagoon ecosystem (approximately 6°N to 6° 38'N) during the December – January period when cloud cover in the area is a minimum.

Information on LST and NDVI was obtained from the three year period of Landsat datasets (1990, 2002 and 2015). The result of regression analysis performed on the two variables is displayed in Figures 4.30 – 4.38. Two distinct relationships between the LST and NDVI can be identified: one with the typical negative slope, indicative of limited vegetation growth; and the second with a small positive slope, this is similar to one of the trend identified by Karnieli *et al.,* (2010), indicating little variability in LST over a spatial range of NDVI. The negative LST-NDVI relationships indicate the basis for less vegetation which Sun & Kafatos (2007) referred to as basis of drought indices in the result of their work. To ascertain whether the slope LST versus NDVI gradually varies with longitude for both the northern and southern region of the Lagoon ecosystem and likewise with latitude for the western region, the average LST and NDVI of some points (west-east direction for both north and south region and south to north direction for the western region) were extracted for each of the years considered in the study. Except for 1990, the slopes gradually decrease from negative to positive from the west eastward and from the south towards the north (north-south region and west region respectively). In 1990, along the west-east and south-north transects, only the western region area (Figure 4.31) showed positive correlation; while the correlations at the northern and southern region were significantly negative. In 2002 and 2015, the correlations were found to be significantly negative for all the regions within the study location in the ecosystem.

Furthermore, to study the spatial patterns of the temporal correlations between LST and NDVI, the correlation coefficient ***R*** was computed in each year in the study area. The negative correlation coefficients (Figures 4.30, 4.32 – 4.38), indicate the moisture green vegetation growth where vegetation health index (VHI) may work well. In each year of the study, NDVI values increase in the west-east direction at the north and south region of the ecosystem. This suggest that vegetation index increases eastward and decrease in urbanisation growth could be inferred. Yet, for the western region of the Lagoon ecosystem, even though the correlation between LST and NDVI is negative, the pattern of correlation here is a decrease in NDVI northward from the south, indicative of a high rate of urbanisation in the south-west region compare to north-west. All the graphs that show the NDVI is negatively correlated with LST imply that areas with least vegetation are experiencing higher land surface temperatures. The lowest values of NDVI are found to correlate with regions of high LST, areas of dense urbanisation with no vegetation while the highest NDVI values correlate with areas of low urbanisation but high vegetation (Figures 4.39 – 4.41). The results suggest that the land cover changes in the Lagoon ecosystem have a high impact on the temperature regime because the peak of the LST are usually the areas with low or no vegetation cover and the peak of NDVI appears at green vegetation areas such as eastward of Ikorodu and the extreme north western region. Within the ecosystem, the built up areas have comparatively low NDVI values and little vegetation.

In each of the Figures 4.30 – 4.38, coefficients of determination (R^2) were computed in order to have a relative idea of how much variance in LST can be predicted by NDVI. The summary is presented in Table 4.21.

Table 4.21: Coefficient of determination of how much variance in LST can be predicted by NDVI

Year	Spatial Location	(R^2)	Variance in LST predicted by NDVI (%)
1990	South	0.208	20.8
1990	West	0.0052	0.5
1990	North	0.25	2.5
2002	South	0.263	26.3
2002	West	0.0031	0.3
2002	North	0.096	9.6
2015	South	0.381	38.1
2015	West	0.55	55.0
2015	North	0.182	18.2

The apparent change witnessed in Figure 4.31 may be as a result of unpredictable seasonal shift between energy and moisture limited vegetation growth. This might suggest that at the northern region of the ecosystem in 1990, relative humidity, rainfall and near-surface air temperature at this period may be important factors responsible for having a slightly increased LST when NDVI value is high.

Additionally, to identify which of these climatic factors are most strongly related to spatial distributions of R, a multiple linear regression was carried out with R as the dependent variable and rainfall, air temperature and relative humidity, as independent variables. The regression result is summarised in Table 4.22.

Table 4.22: Results of multiple regressions between *R* (dependent variable) and the driving (independent) variables – air temperature, rainfall and relative humidity

	Standard error	Regression coefficient	P-value
Air Temperature	0.11416	0.2725	0.062
Rainfall	0.00160	0.0002	0.881
Relative Humidity	0.01393	0.0002	0.990

The explained variance (coefficient of determination r^2) resulting from the multiple regression is 0.564. Analysis of the coefficient of determination r^2 reveals that air temperature has the strongest effect on R. The effect of air temperature was more pronounced among the three climatic factors ($r^2 = 0.275$), indicative that 27.3% of the changes in the LST in the northern region of the Lagoon ecosystem is caused by increase air temperature.

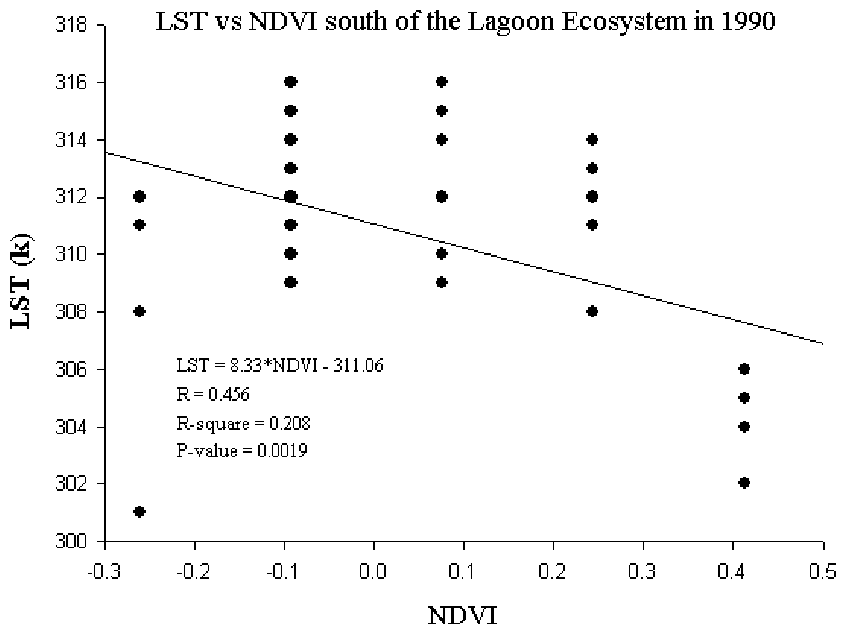


Figure 4.30: LST – NDVI correlation along west – east transect at the southern region of the Lagoon ecosystem in 1990. Note the gradual change of the slope from negative to positive proceeding from west

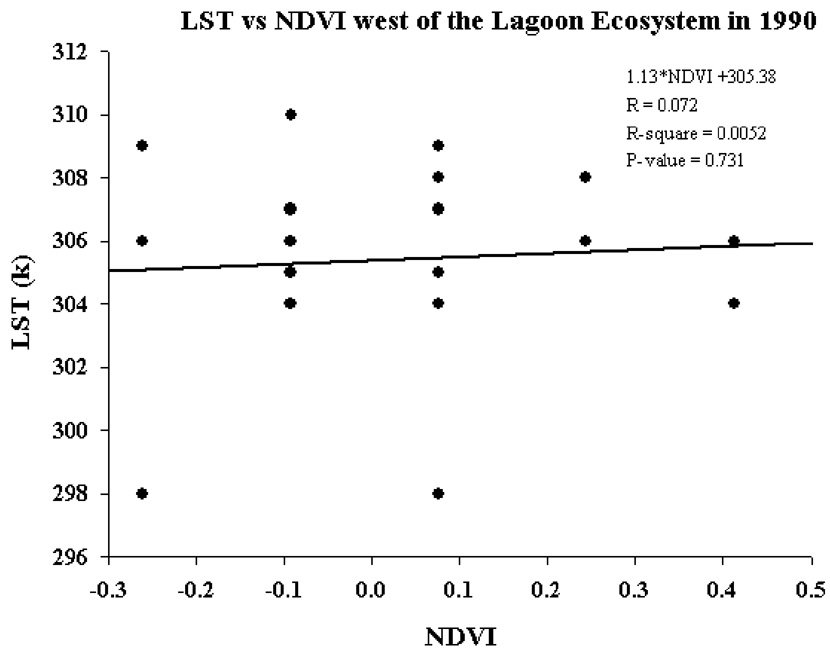


Figure 4.31: LST – NDVI correlation along south – north transect at the western region of the Lagoon ecosystem in 1990. Note the gradual change of the slope from negative to positive proceeding from south

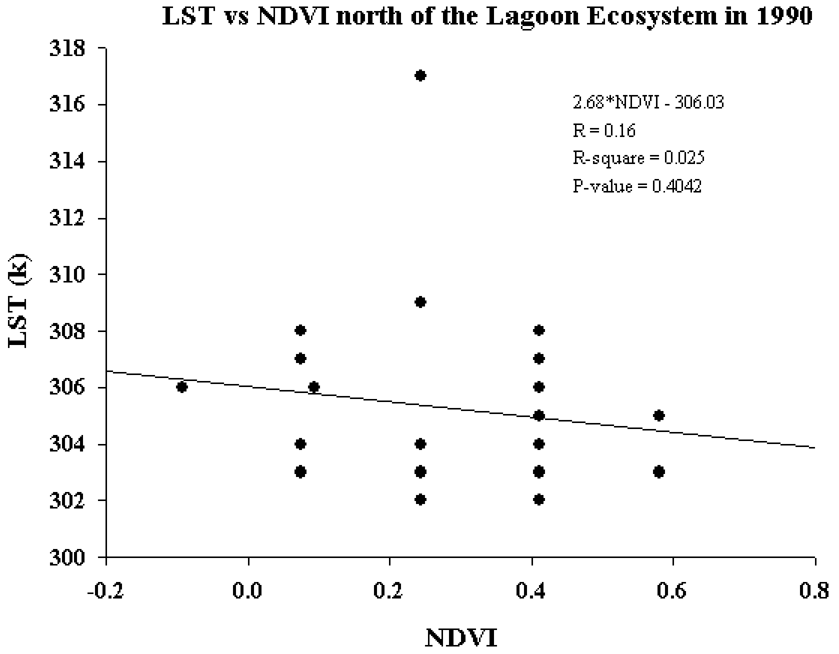


Figure 4.32: LST – NDVI correlation along west - east transect at the northern region of the Lagoon ecosystem in 1990. Note the gradual change of the slope from negative to positive proceeding from the west

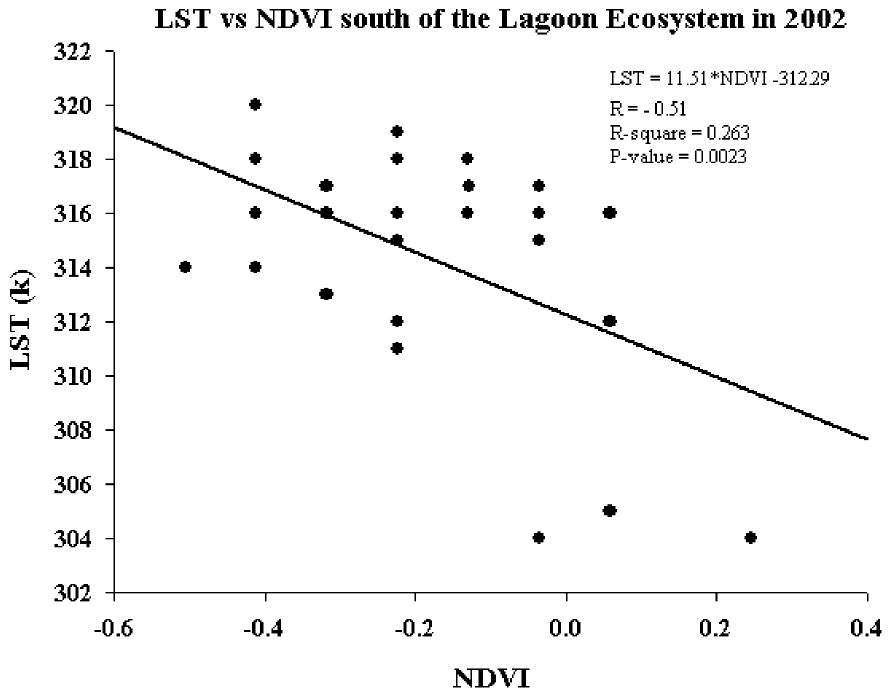


Figure 4.33: LST – NDVI correlation along west - east transect at the southern region of the Lagoon ecosystem in 2002. Note the gradual change of the slope from negative to positive proceeding from the west

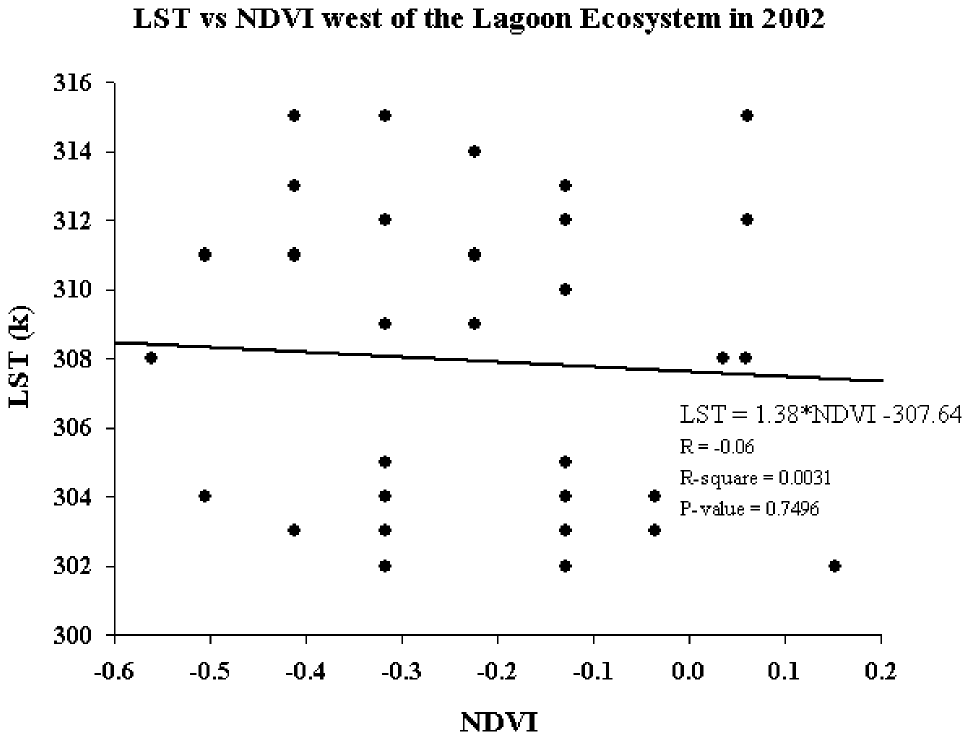


Figure 4.34: LST – NDVI correlation along south - north transect at the western region of the Lagoon ecosystem in 2002. Note the gradual change of the slope from negative to positive proceeding from the south

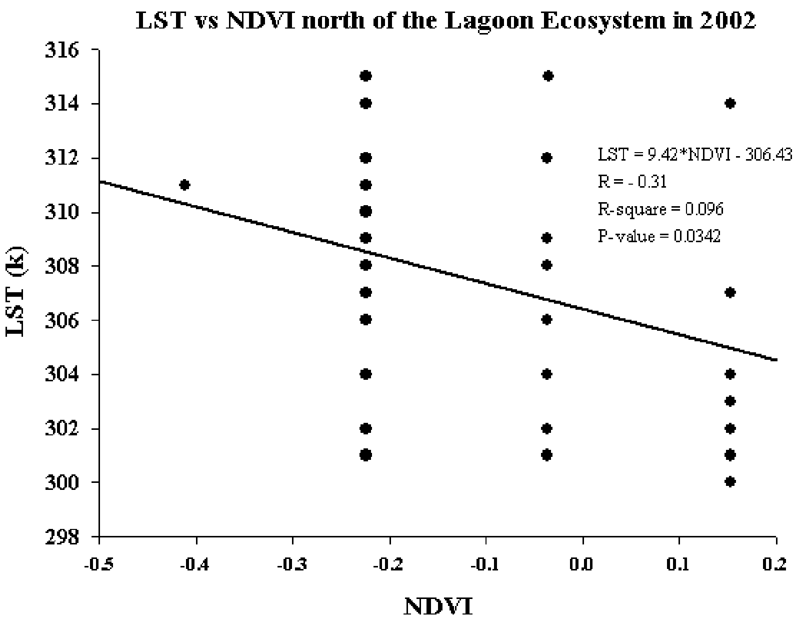


Figure 4.35: LST – NDVI correlation along west - east transect at the northern region of the Lagoon ecosystem in 2002. Note the gradual change of the slope from negative to positive proceeding from the west

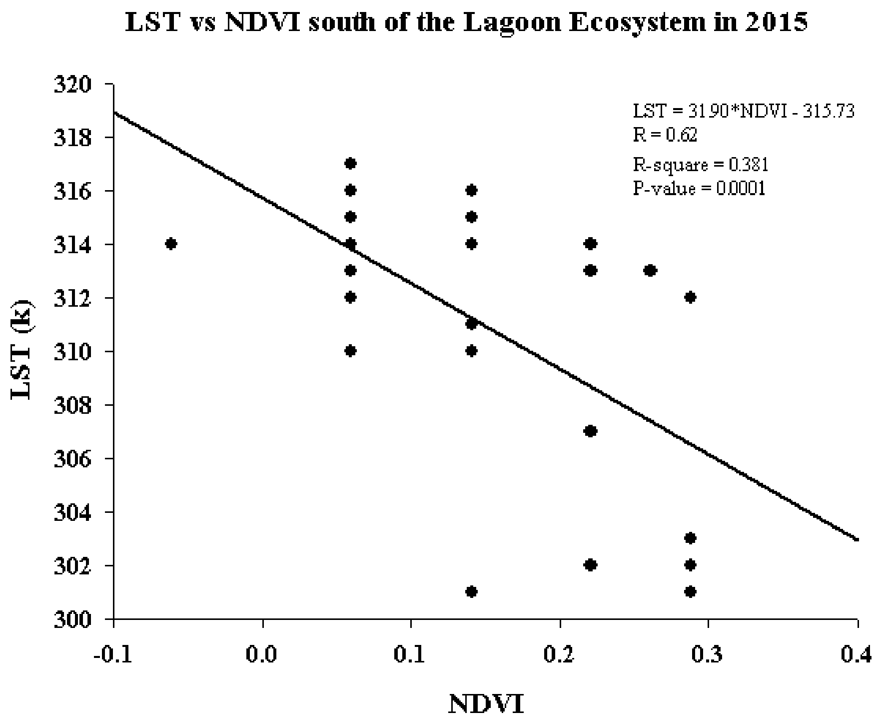


Figure 4.36: LST – NDVI correlation along west - east transect at the southern region of the Lagoon ecosystem in 2015. Note the gradual change of the slope from negative to positive proceeding from the west

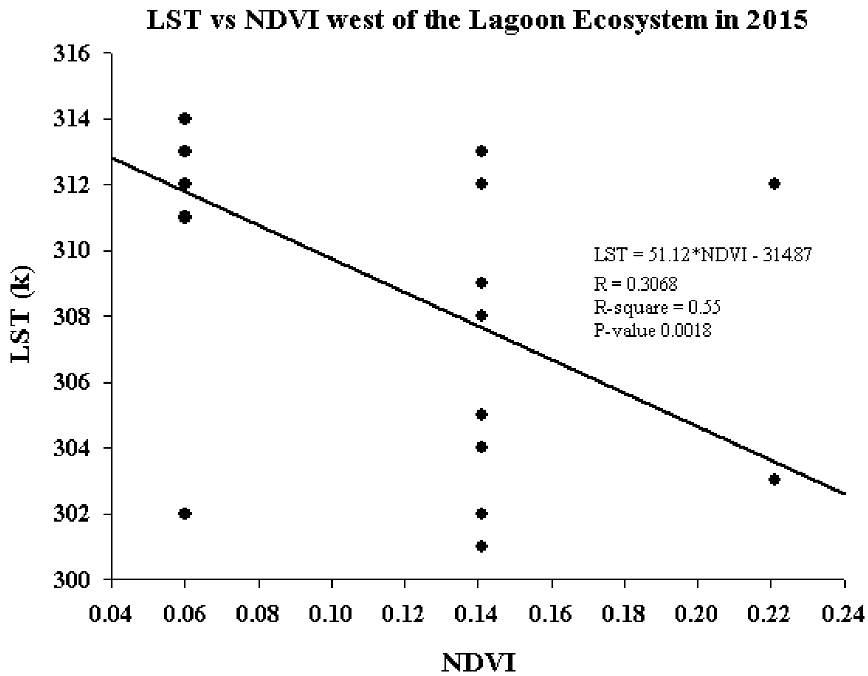


Figure 4.37: LST – NDVI correlation along south - north transect at the western region of the Lagoon ecosystem in 2015. Note the gradual change of the slope from negative to positive proceeding from the south

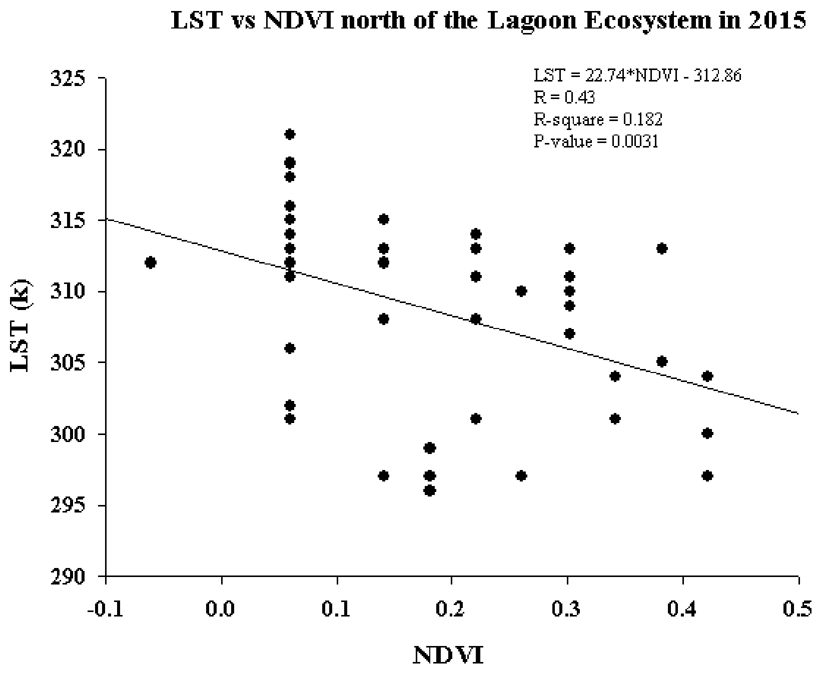


Figure 4.38: LST – NDVI correlation along west - east transect at the northern region of the Lagoon ecosystem in 2015. Note the gradual change of the slope from negative to positive proceeding from the west

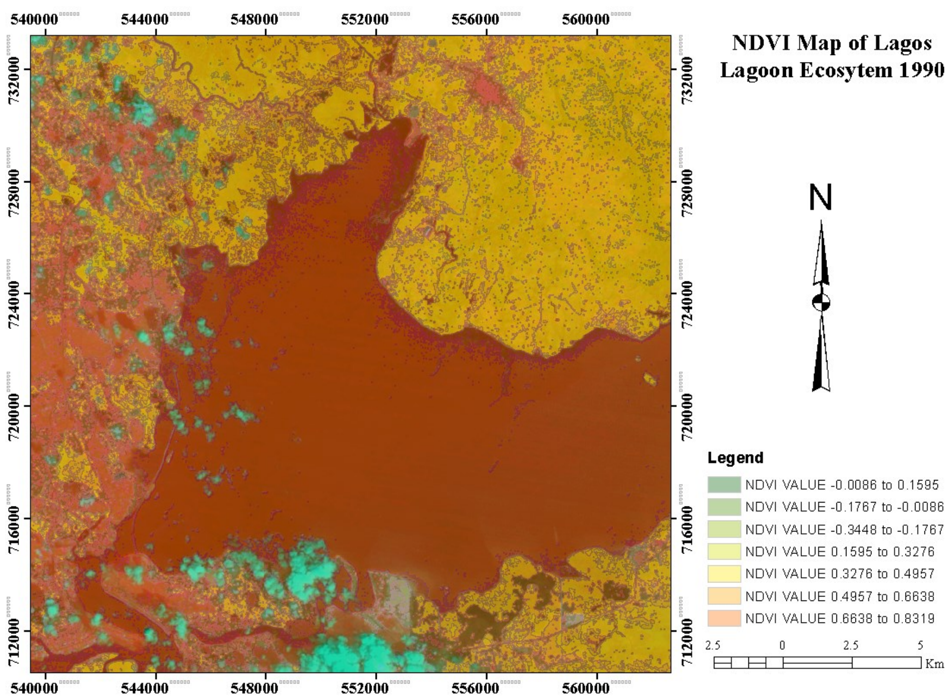


Figure 4.39: NDVI map of Lagos Lagoon derived from Landsat image of 1990

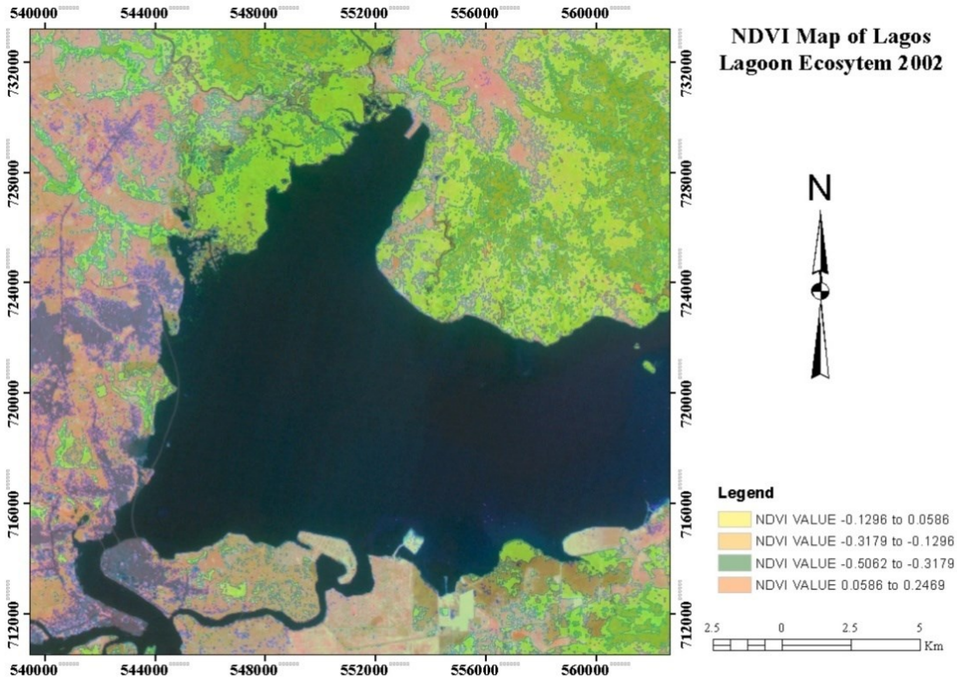


Figure 4.40: NDVI map of Lagos Lagoon derived from Landsat image of 2002

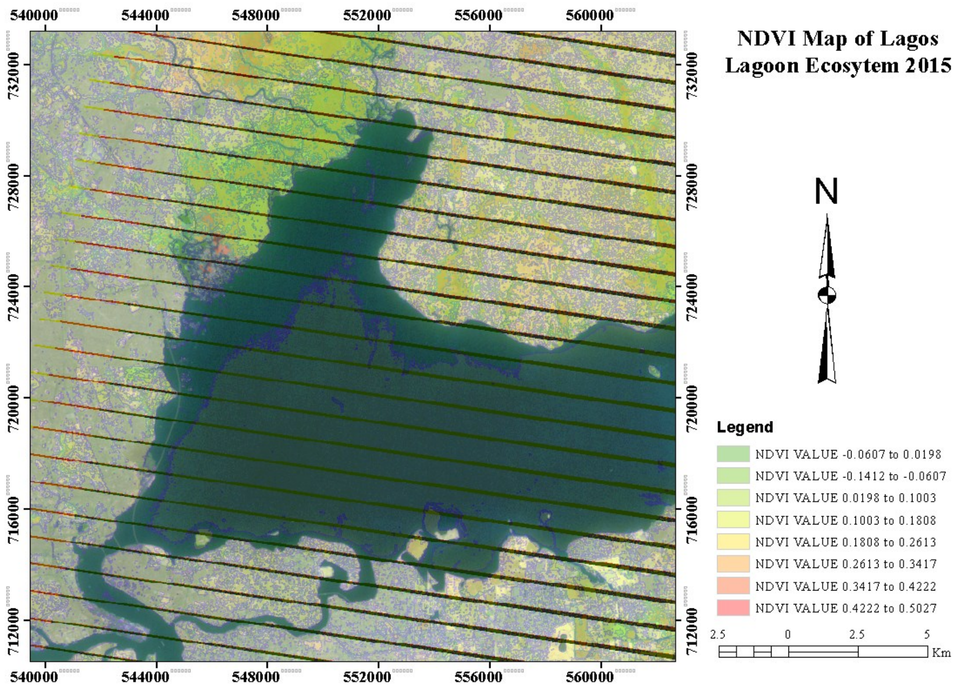
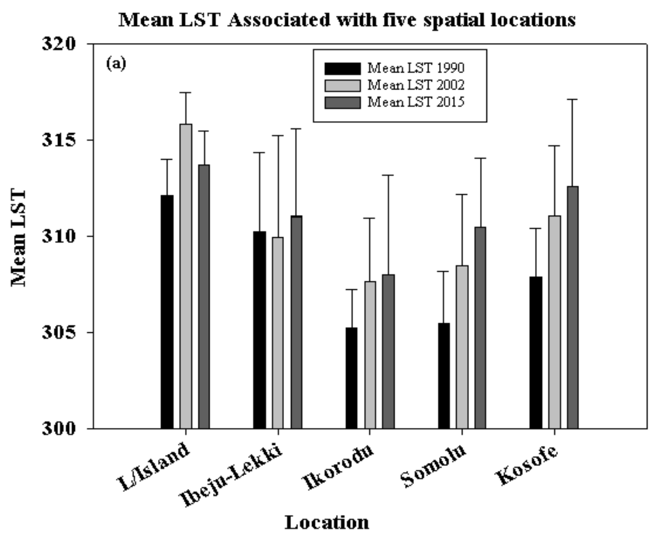


Figure 4.41: NDVI map of Lagos Lagoon derived from Landsat image of 2015

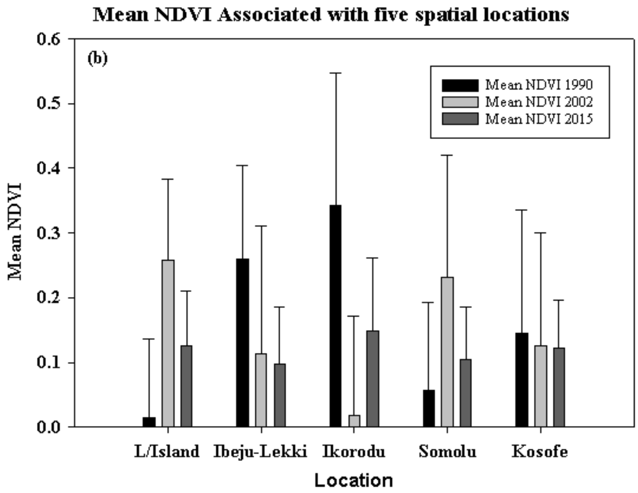
4.11 Difference in mean LST and mean NDVI by land use types

To understand the relationship between LST, NDVI and the land cover type, measurement of central tendency (mean) and dispersion of LST and NDVI associated with land cover type in an area was further analysed. Five different spatial locations were chosen (Lagos Island, Ibeju Lekki, Ikorodu, Somolu and Kosofe) within the Lagoon ecosystem; these are areas with different degrees of urbanisation.

Figures 4.42a and 4.42b depict mean LST and NDVI values associated with each of the five spatial locations, with error bars representing ± 1 standard deviation. From the Figures, Lagos Island and Somolu areas show the highest mean LST values possibly because of high rate population and urbanisation of the area which invariably bring about large amount of human induced heat. Because of high rate of urbanisation in these areas, average LST in each of the year of study is higher; this is one of the effects of Urban Heat Island (UHI). Notwithstanding, areas like extreme eastern part of Ikorodu and Ibeju-Lekki exhibit the highest mean NDVI value, Figure 4.42, because of predominance of vegetation cover. In agreement with the findings of Wilson *et al.,* (2003) and Yue *et al.,* (2007) green vegetation cover in the areas suggest relatively higher rates of evapotranspiration and favouring of latent exchange between surface and atmosphere as compared with built up areas. From figures 4.40, it can be seen vividly that mean LSTs and mean NDVIs have clear differences with each of the chosen area as associated with dominant land cover type.



(a)



(b)

Figure 4.42: Mean values of (a) LST and (b) NDVI associated with the dominant land-cover in five spatial region of the Lagoon ecosystem

4.11.1 Multiple comparison of mean

Added to the information in this section, five spatial locations were chosen where (i) urbanisation has reached almost saturation level and (ii) urbanisation is still increasing exponentially. This is to ascertain if there is significant variation in the mean of the LST and NDVI by pairing the variables at these locations. To gain further insight, a multiple comparison tests were conducted to disclose the significance of differences in mean LST and NDVI measurements associated with the five spatial areas and their dominant land cover type. The multiple comparison test decrease the chance of Type I error for multiple tests by adjusting α (the significant level) as a function of sample size and number of tests completed. The summary of the result of the comparison test is displayed in Table 4.22. Of the ten possible combinations of detailed spatial locations for NDVI and LST respectively, none of the pairings displayed significantly different mean values. Hence the spatiotemporal distributions of these variables (NDVI and LST) in the five spatial locations show that changes in the NDVI and LST occur at almost the same rate. Overall, multiple comparisons of means indicated that almost all the spatial locations around the Lagoon ecosystem did not show any significant difference on the basis of NDVI and LST comparison. This is an indication that the exponential increase in human population around the Lagoon ecosystem is not peculiar to a particular area of the ecosystem but it is an occurrence that is general to the entire system.

Table 4. 23: Results of multiple comparison tests to evaluate significance of difference in (a) mean NDVI and (b) mean LST values associated with five spatial locations around the Lagoon ecosystem

(a) Multiple comparison table of mean differences in NDVI for five spatial locations					
	L/Island	Ibeju-Lekki	Ikorodu	Somolu	Kosofe
L/Island	1				
Ibeju-Lekki	0.740	1			
Ikorodu	0.657	0.993	1		
Somolu	0.988	0.837	0.767	1	
Kosofe	0.936	0.930	0.880	0.980	1
(b) Multiple comparison table of mean differences in LST for five spatial locations					
L/Island	1				
Ibeju-Lekki	-0.335	1			
Ikorodu	0.749	0.374	1		
Somolu	0.525	0.626	0.957	1	
Kosofe	0.595	0.558	0.978	0.996	1

*the mean difference is significant at the 0.05 level

4.12 Spatiotemporal changes on the Lagoon coastline

The several effects ranging from urban explosion, increase LST, depletion in swamp and vegetation, on the Lagoon ecosystem are believed to have subsequent effect on the coastline of the Lagoon. Hence, this section is the results of the Model developed in GIS to measure the extent of change experience along the coastline within a period of 26 years (1990 -2016). Landsat image of 1990, 2002, 2006, 2011 and 2016 were used from which the coastline of the Lagoon in each of the year was delineated and uploaded to the model as union dataset. Table 4.24 and Figure 4.43 show the summary results of the extent of the Lagoon water that has been reclaimed as at January 2016; this was compared with the population rate in Lagos state. It was revealed from Figure 4.43 that the rate of reclamation along the coastline increases more as population was increasing. This is to suggest that available space for further development or for urban expansion is already filled up hence the only option is to gradually encroach into the Lagoon in order to create more land for urban expansion.

The result from Figures 4.43 - 4.45 revealed that during the period of 1990 – 2011, excessive reclamation was experienced along the Lagoon coastline. Going by the trend of population growth rate against year in Figure 4.43, the area of reclamation experienced in 2011 supposed not to be as high as 14718323.780 m^2. This suggests that excessive reclamation must have taken place within this period.

Table 4. 24: Area reclaimed along the Lagoon coastline during the four years period from 1990-2016.

Range of year	Area of the coastline reclaimed (m^2)	Year	population
1990 - 2002	7662150	2002	7466788
1990 - 2006	11341345	2006	9113665
1990 - 2011	14718324	2011	9735337
1990 - 2016	15125170	2016	11114432

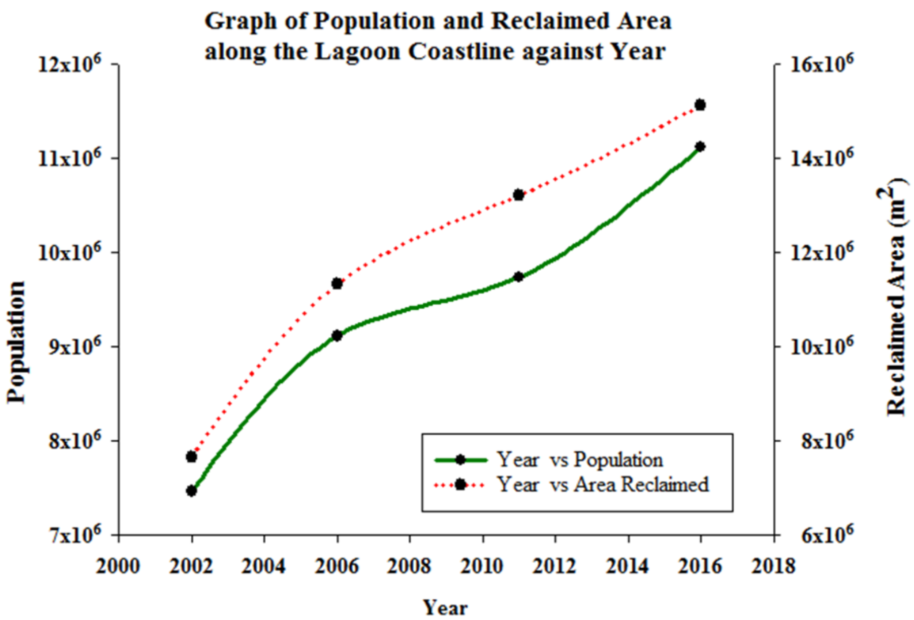


Figure 4.43: Graph of Lagos population and area reclaimed portion along the Lagoon coastline. The gradient of the slope of reclamation is higher than that of population, indicative that space for expansion is almost becoming saturated showing that the only alternative to create more space is to reclaim part of the Lagoon and convert it to land for development

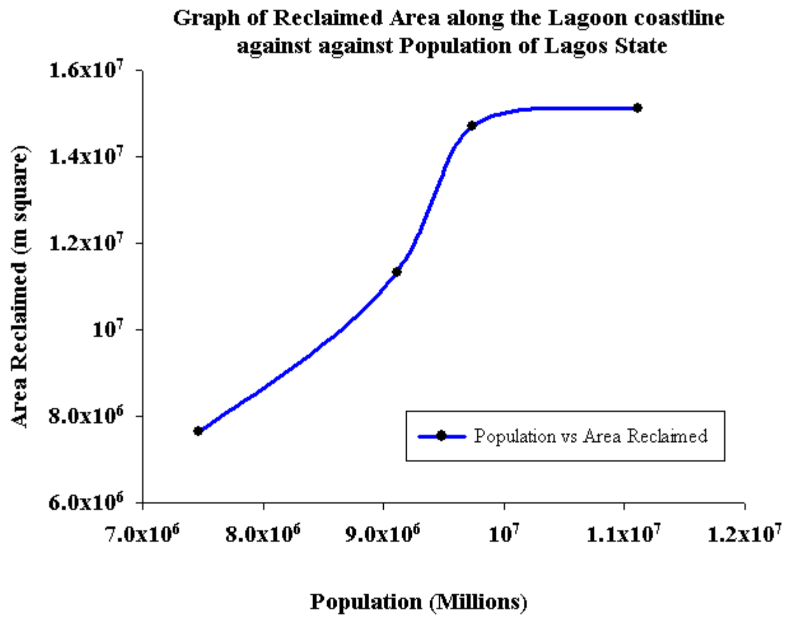


Figure 4.44: Graph of Reclamation along the Lagoon coastline against population growth in Lagos State. Between 2002 and 2011 when population of the state were 7.5 million and 11.1 million respectively, there was an exponential increase in the rate of reclamation, but from 2011 to 2016 the rate decrease

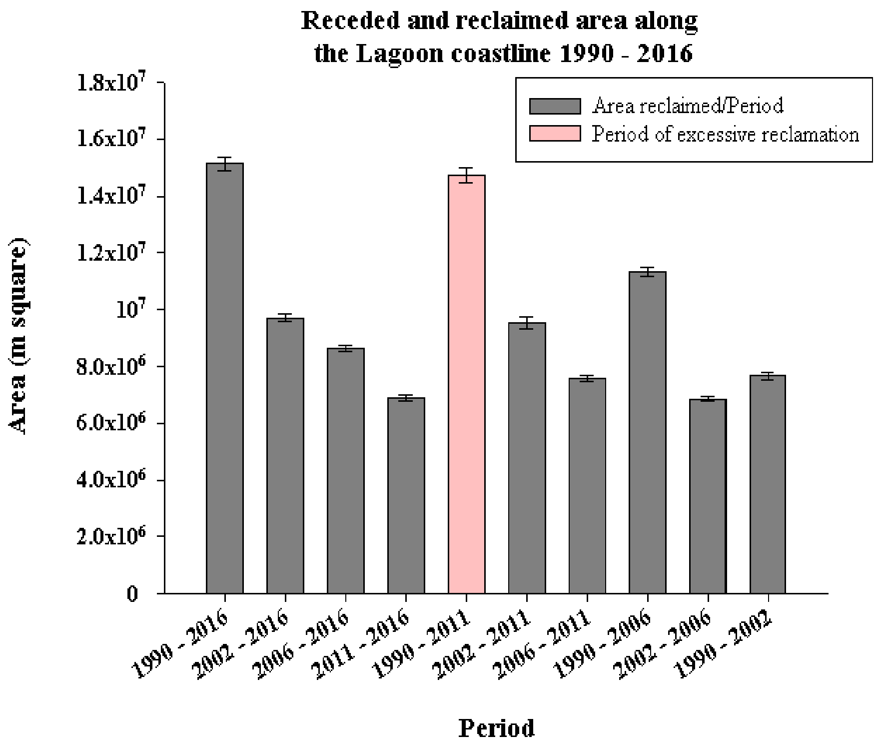


Figure 4.45: Graph showing significant variation in the amount of area reclaimed along the Lagoon coastline at different periods. (a) The pink bar shows the period of excessive reclamation. (b)Bars with grey colour indicate period of progressive reclamation when comparing population growth rate with the rate at which reclamation occurred with specific period

Between the periods 1990 to 2016, significant variation has taken place in the Lagoon coastline, the standard deviation error bars of each period in Figures 4.45 and 4.46 were not overlapping at any point. This reveals that there is statistically significant variation in the amount of area reclaimed from the Lagoon water. This variation kept increasing exponentially from 1990 to 2016. Between 2006 and 2011, the result from Table 4.24 reveals that the portion of the Lagoon that has been turned to coastland is almost half of the total area reclaimed between 1990 and 2016. It could be inferred from this result that exponential population growth witnessed in Lagos since 1984 (Table 4.23) till date has caused direct change on the natural coastline of the Lagoon.

This study reveals that a total of approximately 15125170m^2 (15.125km^2) has been reclaimed from the lagoon water to coastland between 1990 and 2016. This indicates that the Lagoon surface area is gradually reducing from what it was claim to be. If the claim of Balogun *et al*., (2010) is anything to go by, the Lagos Lagoon surface area is approximately 208km^2 as at 2010, the result of this model calculation suggest that the entire surface area of the Lagoon as at moment most have reduced to approximately 204.51km^2. Hence, this model is a useful engine to monitor changes along any lagoon coastline especially in areas of unplanned coastal development; the monitoring could help to suggest mitigating measures in securing the natural existence of the lagoon coastline.

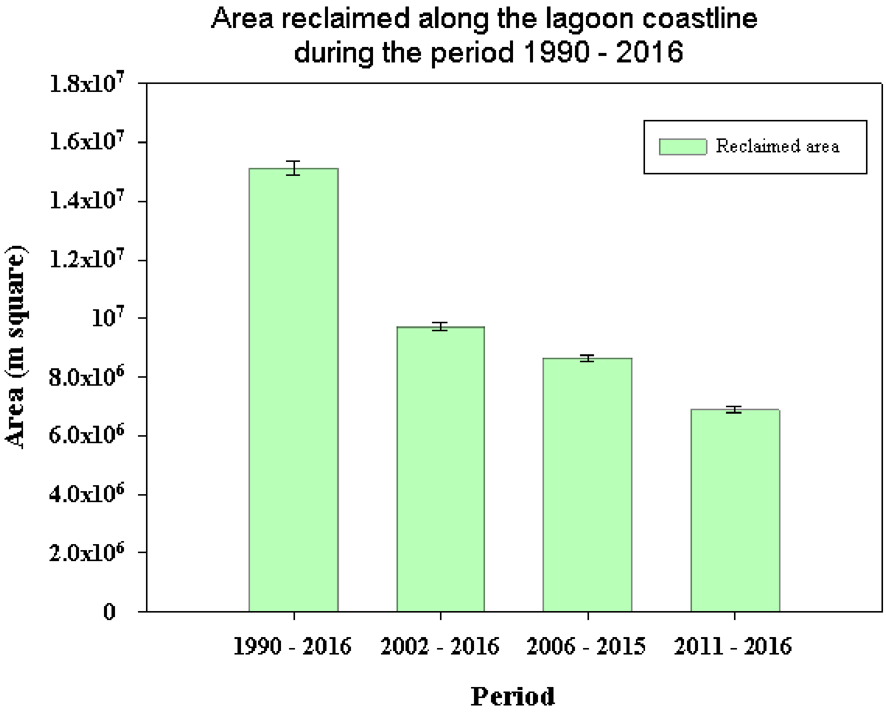


Figure 4.46: Significant variation in the amount of area affected along the lagoon coastline as a result of reclamation between 1990 -2016

4.12.1 The affected part of the Lagoon coastline

It is very important to know areas that are highly vulnerable to reclamation and recession along the coastline as a result of urban expansion. This model was able to reveal spots of reclaimed areas and areas of recession within the period of the study. The result show reclaimed areas in red colour, Figure 4.47. The model first performs union operation by combining all the coastlines involved in the modelling. In order to see the changes that occur within a period of 1990 and 2016, the model simulates the two coastlines 2016 by dissolving the two datasets and then depict the result as region present in 1990 but absent in 2016. Such affected area appeared in the Figure as red colour.

The unchecked reclamation along the coastline affected majorly the western and southern region of the Lagoon, Figure 4.48; the affected part in the north and east were not as much as in the west and south. This confirms one of the assertions made in sections 4.5 and 4.8 that population and urban growth has almost reach a saturation point at the southern region of the Lagoon ecosystem. Contrariwise, the eastern part of the lagoon coastline did not experience much change in terms of reclamation (Figure 4.49), this may be as a result that much population and urban settlements are not concentrated on this area.

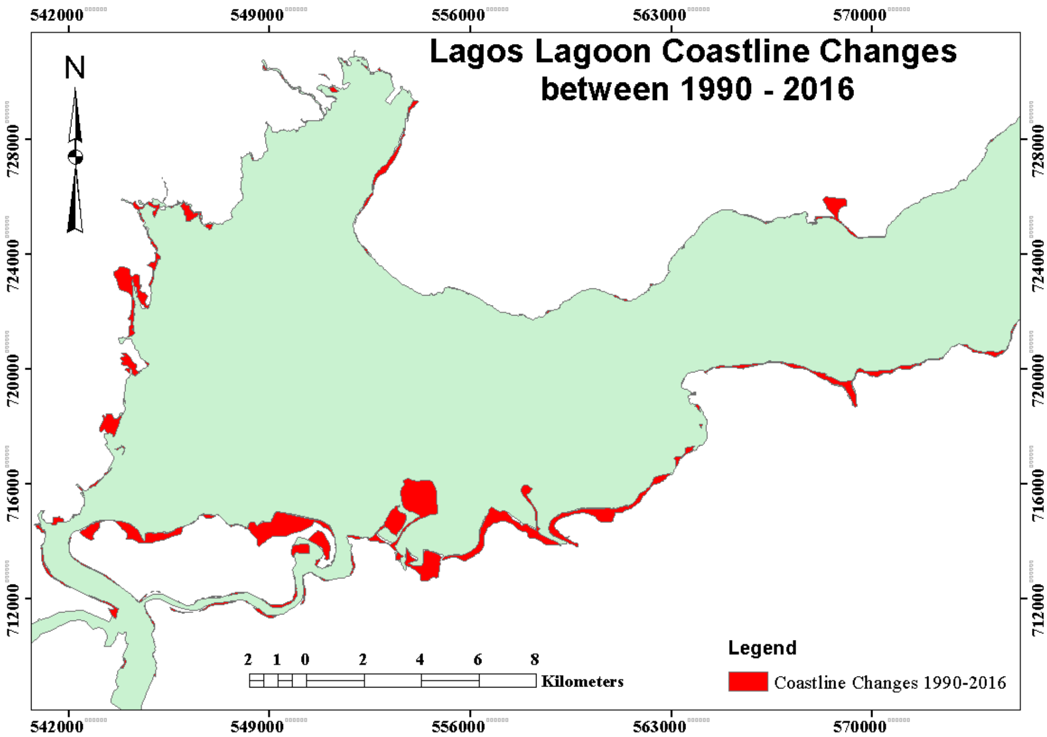


Figure 4.47: Part of the Lagos Lagoon showing areas where the Lagoon water has been converted to coastland. The areas depicted in red colour are regions that were former covered by water but it's now converted to land as a result of reclamation

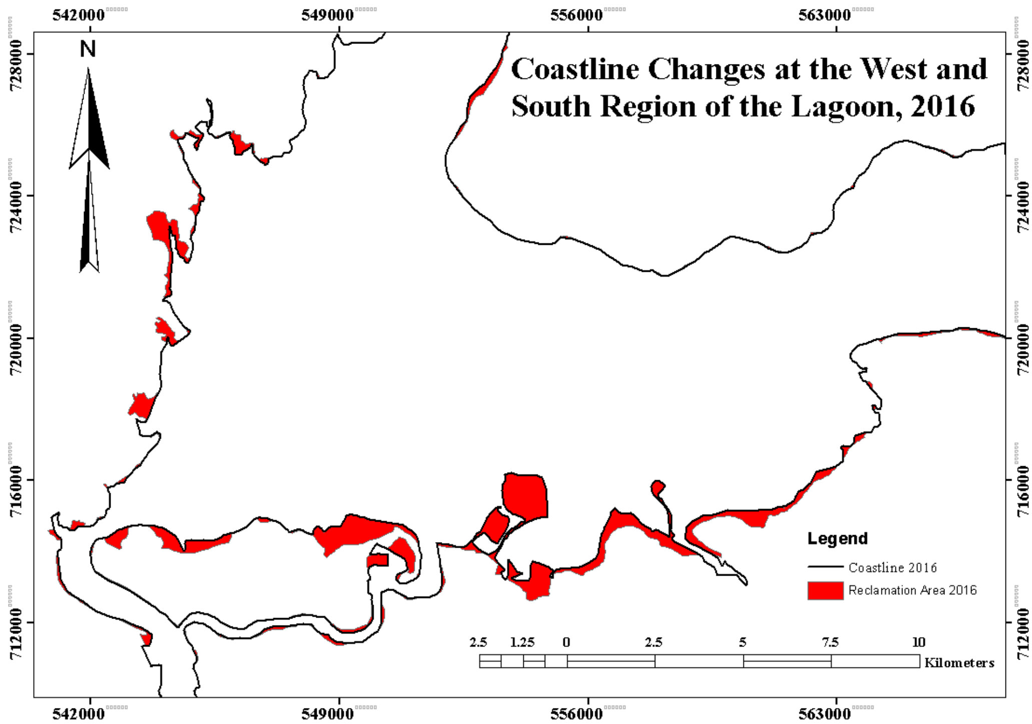


Figure 4.48: Coastline changes at the west and south region. Almost every section of the Lagoon coastline was shifted inside to the Lagoon water to reclaim part of the Lagoon water to coastland

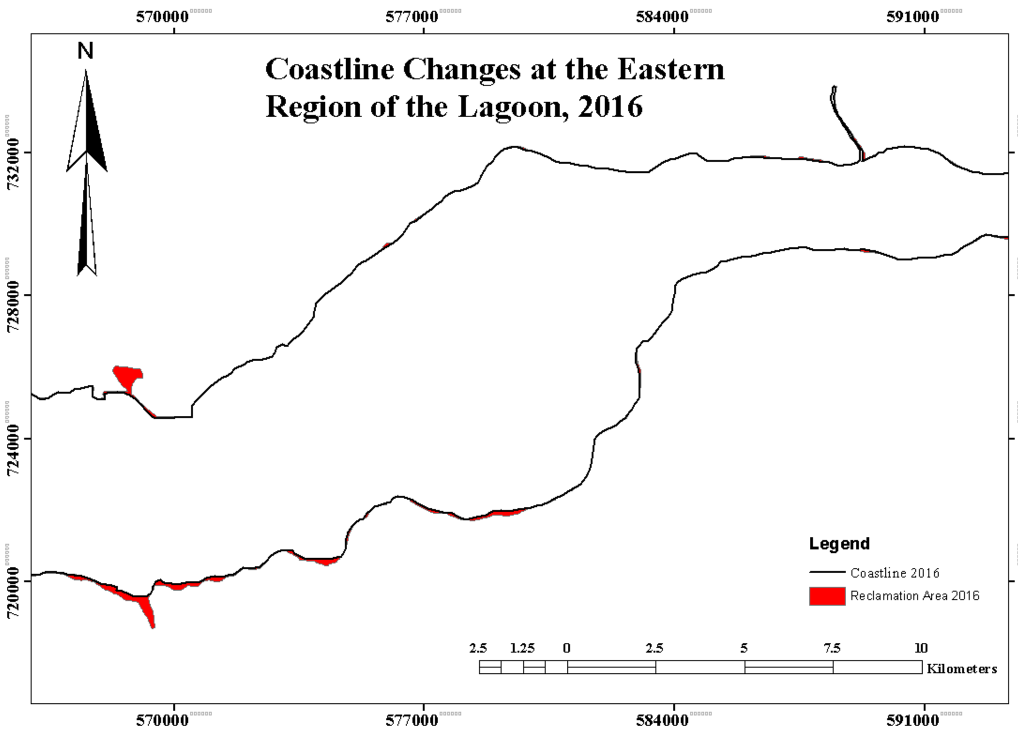


Figure 4.49: Map showing reclaimed area along the eastern part of the Lagoon coastline. The region that appeared in red colour in the map denotes areas that were formerly occupied by water but has been filled and converted to coastland

Conversely, the action of predominant reclamation at the western and southern region along the Lagoon coastline produces opposite reaction of recession; this was very prominent in the north east area. This result could be liken to the conceptual sediment balance suggested by Bentum *et al.,* (2012) where increase impact of long term erosion on the eastern part of Lagos Atlantic coast was a resultant action of excessive accretion on the western side of the coast. The model was also able to simulate the coastline of 1990 and 2016 and show areas where the Lagoon water receded and turn coastland to waterbody, Figures 4.50, 4.51 and 4.52. The reclamation being prominent in the south and west region as a result of increased urbanisation tends to be pushing the Lagoon water eastward in order to find space. This endangers the eastern part of the coastline and it will also makes development along the coastline vulnerable to flooding.

Furthermore, the total area reclaimed was compared to the area by which the Lagoon water receded to gain space as at January 2016. It was discovered from the model result that so far 15,125,169.842m^2 (15.13km^2) has been reclaimed from waterbody and turned to coastland along the Lagoon coastline. However, the Lagoon water has receded and covers a total of 421,4994m^2 (4.21km^2) from the Lagoon coastland. This suggests that the ratio of reclamation to that of recession along the coastline is approximately 4 to 1 (4:1). This means for every one square kilometre of coastland claimed by the lagoon water, a total area of four square kilometres is reclaimed as coastland. The rate of reclamation is far more than the rate at which the Lagoon water receded, the ratio also gives a clue that the Lagoon is highly vulnerable to extinction if this ratio continues and invariably increased as population increases. This inference, the near syndrome to extinction, is also affirmed in chapter five as investigation into the Lagoon sea-bed dynamic is considered.

Figures 4.50 – 4.52 revealed that recession of the lagoon water occurred mostly in the north and west. One of the devastating effect that results from the recession was the flooding that occurred in 2011 (Etuonovbe, 2011) where several properties were lost by the people living some few kilometres from the Lagoon coastline around the region where River Ogun enters the Lagoon. The flooding might have been empowered as a result of the significant recession along the Lagoon coastline at this part of the Lagoon.

In four different spatial areas at the north, west, south and east, reclamation was compare to recession along the coastline and the summary result is in Table 4.25. From this result, ratio of reclamation compared to recession is very high in the south and west (ratio 5:1) where there is saturated urbanisation. This is confirmatory evidence that support one of the results in sections 4.4 – 4.8 that swamp, mangrove and vegetation along the Lagoon coastline are depleting fast. Alternatively, along the east coast the opposite was the case in term of reclamation compare to recession (ratio 1:2); more recession was witnessed around this region than reclamation. While at the north region the ratio is 1:1, Figure 4.53. The graph in Figure 4.54 reveals a reduction pattern in the trend of recession along the coast from north to west and then the rate started increasing from the south region and attained maximum at the east. However, reclamation increased from the north and attained maximum in the south region and started decreasing towards the east.

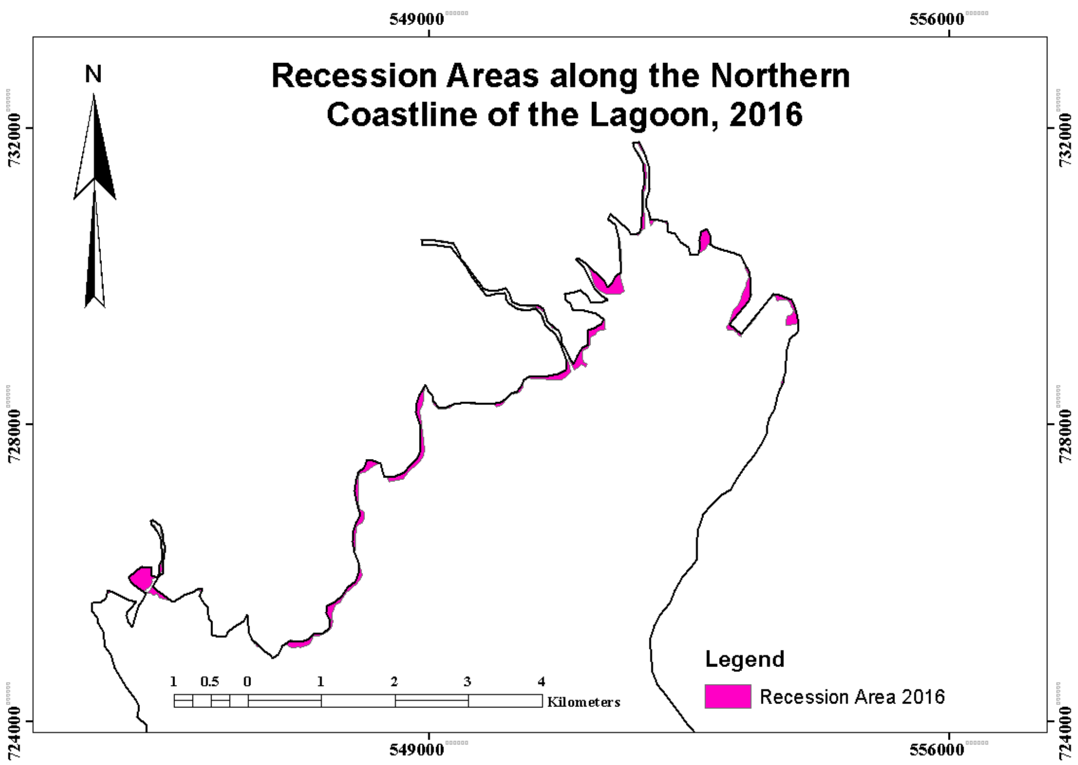


Figure 4.50: Part of the Lagoon showing areas where coastland is converted to water in the northern region. The area in pink colour revealed from the model area of coastland that has been transformed into waterbody

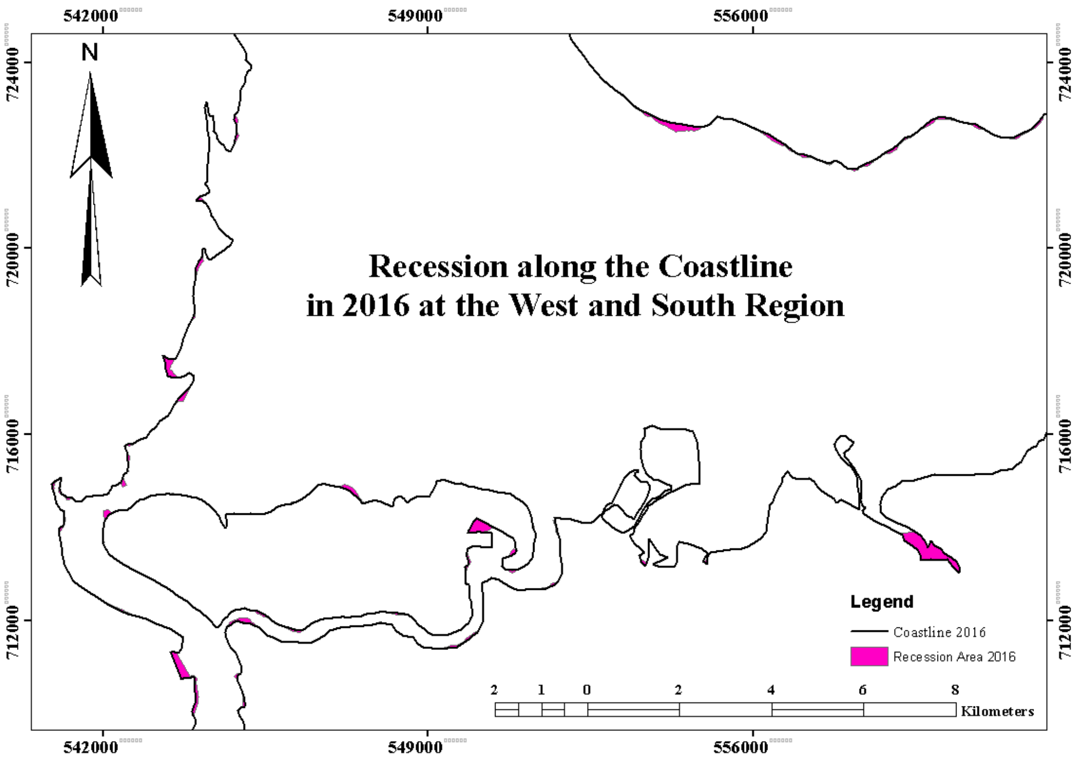


Figure 4.51: Map showing recession area of the Lagoon coastline at the south. Less recession occurred compared to the volume of reclamation

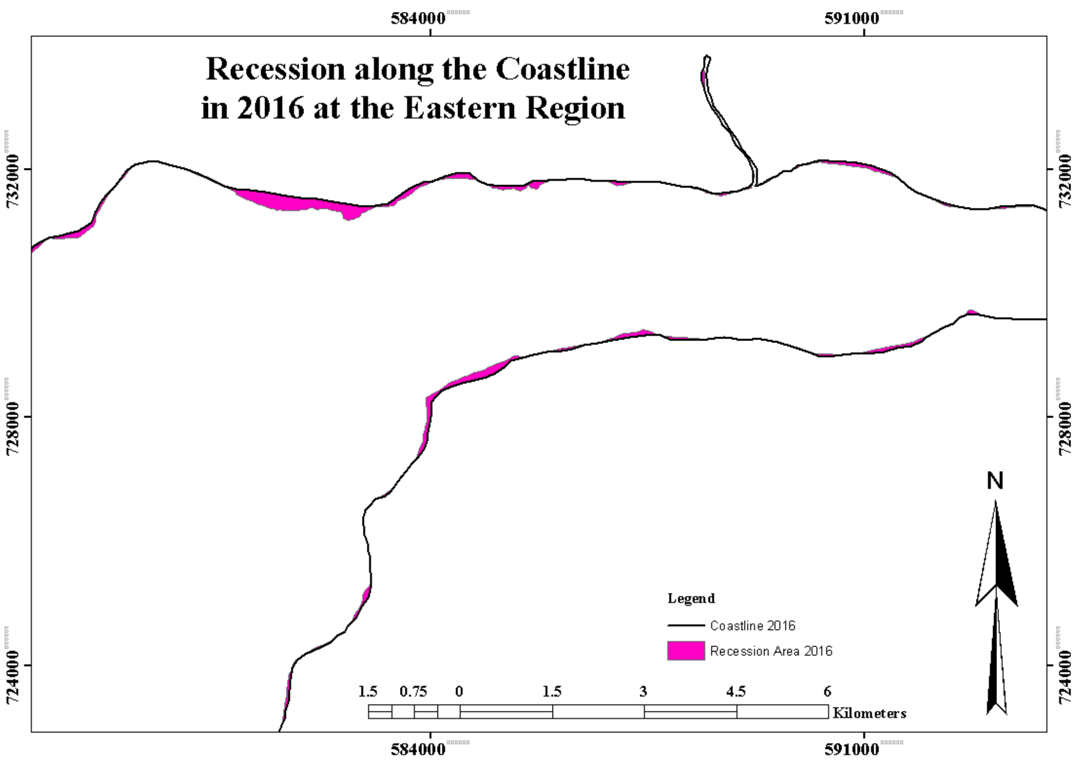


Figure 4.52: Map showing recession area of the Lagoon coastline at the east. More recession occurred in the east than reclamation

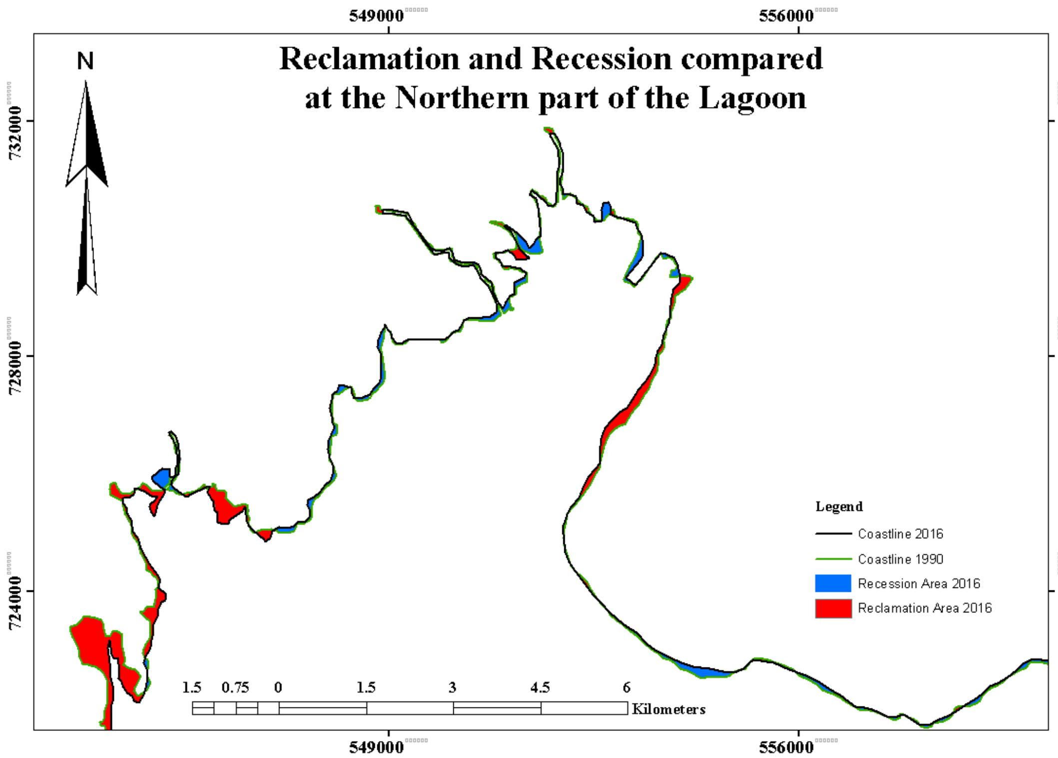


Figure 4.53: Map showing recession and reclamation area at the northern region of the of the Lagoon coastline. The occurrence of the two phenomena is approximately in ratio 1 to 1

Table 4.25: Recession and reclaimed region of the Lagoon coastline as at January 2016, this is compared in four spatial regions. The Table also shows ratio of reclamation in each of the spatial area to that of recession

Spatial Region	Area Receded (m^2)	Area Reclaimed (m^2)	Ratio
North	29317.401	21181.00	1:1
West	6360.864	29866.69	5:1
South	16197.972	74556.97	5:1
East	43400.160	24008.660	1:2

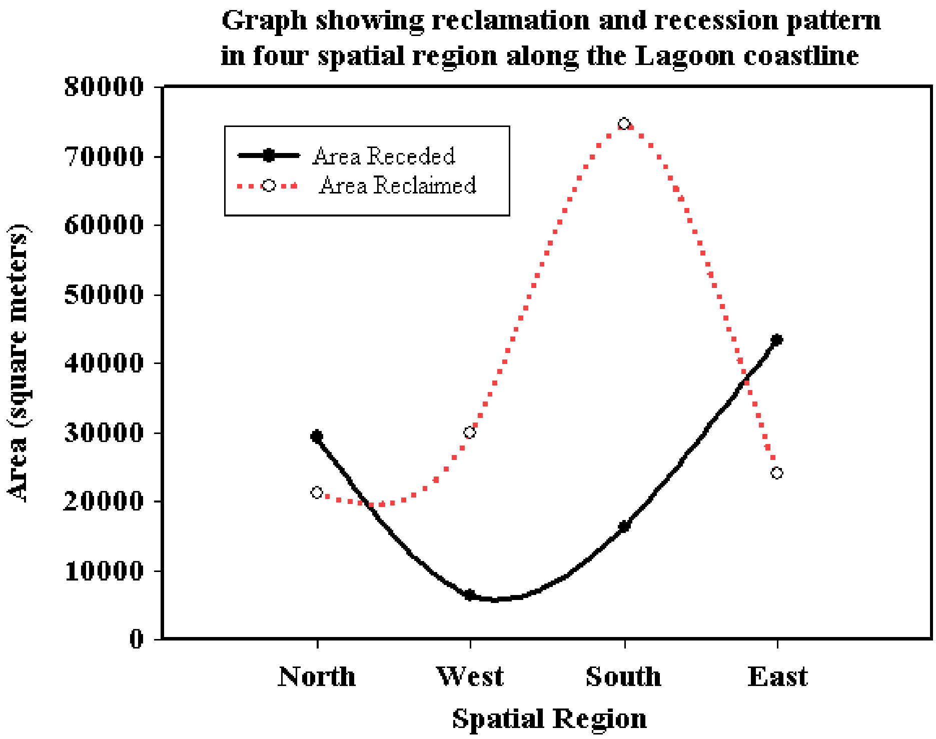


Figure 4.54: Trend pattern of reclamation and recession in four spatial regions along the Lagoon coastline

4.13 Summary

The overriding purpose of this chapter was to determine the relative morphological changes induced within the Lagoon ecosystem by investigating the main land use classifications, mangrove, swamps, built-up area, vegetation and bare-land. In overview, the results show that the amount of the mangrove, vegetation and swamp in the Lagoon ecosystem depleted in correlation to the increase built-up area. However, the impact of the changes was further investigated using the LST and NDVI indicators, and the outcome exhibits that the western region of the Lagoon ecosystem as having high LST and low NDVI, but the LST was reducing towards the eastern region while the NDVI was increasing. More also, the result of the investigation in the section revealed that the Lagoon surface area has been reduced by approximately 15125170km^2 reducing it from 208km^2 (Balogun *et al.,* 2010) to 204.51km^2 through reclaimed between 1990 and 2016.

4.14 Conclusion

In summary, the results from this chapter have confirmed that the Lagos Lagoon ecosystem and its coastline are changing rapidly. More than half of the wetland in the ecosystem has been converted to either built-up area or impervious land. It is worthy of note that Nigeria accounted for 36.67% of the total mangroves that exist in 19 coastal African nations with a coverage area of 7386km^2 (Oyebade *et al.,* 2010). The rate of dissipation of the wetlands along the Lagos Lagoon coast calls for concern and immediate control of further destruction of the wetlands. The wetland has been compromised leading to exposure of the entire ecosystem to immediate environmental danger and degradation, this call for a serious concern. Ogundipe in the article of Akoni (20014), Nigerian Vanguard Newspaper, visualised from an historical perspective that there is need for immediate preservation of the Lagoon wetlands. He noted this as an option for life and living because considerable amount of natural surface replaced with impervious surface will generate serious environmental stress and bring negative effect on urban micro-climate. Hence this statement can be justified based on the results from this section of the research that serious intrusion into the Lagoon ecosystem and along its coastline is on-going. Hence urgent attention is needed by the government to rescue the Lagoon and restore the damaged ecosystem.

Secondly, the results also revealed the impact of unchecked increased population growth and unplanned environment on a coastal Lagoon. It was confirmed from the results that the Lagoon coastline has been seriously encroached into thereby reducing the surface area of the Lagoon. Hence, near disappearance syndrome is a glaring phenomenon for the Lagoon if urgent mitigation measure is not applied to this incessant encroachment.

Moreover, this section of the study has been able to answer one of the research questions on what is the spatial and temporal variability of coastal urban expansion impact on

Lagoon ecosystem. It has been verified that the natural pattern of the Lagoon ecosystem is changing and this alter the natural morphology of the Lagoon coastline.

Conclusively, the first objective of this research has been solved, because the extent and impact of urbanisation on the Lagoon ecosystem and its coastline has been determined. The method applied in getting these results, though localised to Lagos lagoon, can be applied to any lagoon globally, especially those lagoons that exist in coastal countries where there is no control and plan for urbanisation along the coastal zone.

CHAPTER FIVE
MEASURING AND MONITORING THE LAGOON SEABED DYNAMIC

5.1 Introduction

The changes on the Lagoon water bed over six years' time scale using repeated bathymetric data (2008 and 2014) was presented in this chapter. In overview, it presents a basic understanding of bathymetry as a process of acquiring the bathymetric data that was used in the research. The procedure of the bathymetry and data reduction is followed by analysis of the Lagoon water bed dynamics using abstracted profile lines from the bathymetric data. However, the results of the significant accretion and erosion inside the Lagoon were analyzed spatially to quantify the volume of sediment gain or loss on the Lagoon water floor. This enhanced the possibility of verifying if the Lagoon is disappearing gradually. This aspect of the research, to the best of the author's knowledge, reveals for the first time the various kinds of evolutionary changes (channel movement, accretion, erosion, infill and movement of shoal) on the Lagoon water bed.

In general, the Lagoon system and its adjacent tidal basins exhibit dynamics which are significantly different on both spatial and temporal scales. This is expected from a semi-diurnal tidal regime; as urbanisation and human activities around the Lagoon increase, and the volume of sediment that is entering into the basin is believed to be increasing on a daily basis. Figure 5.1 shows the survey boat used with the single beam echo sounder for collection of bathymetric data on Lagos Lagoon during the 2014 data gathering.

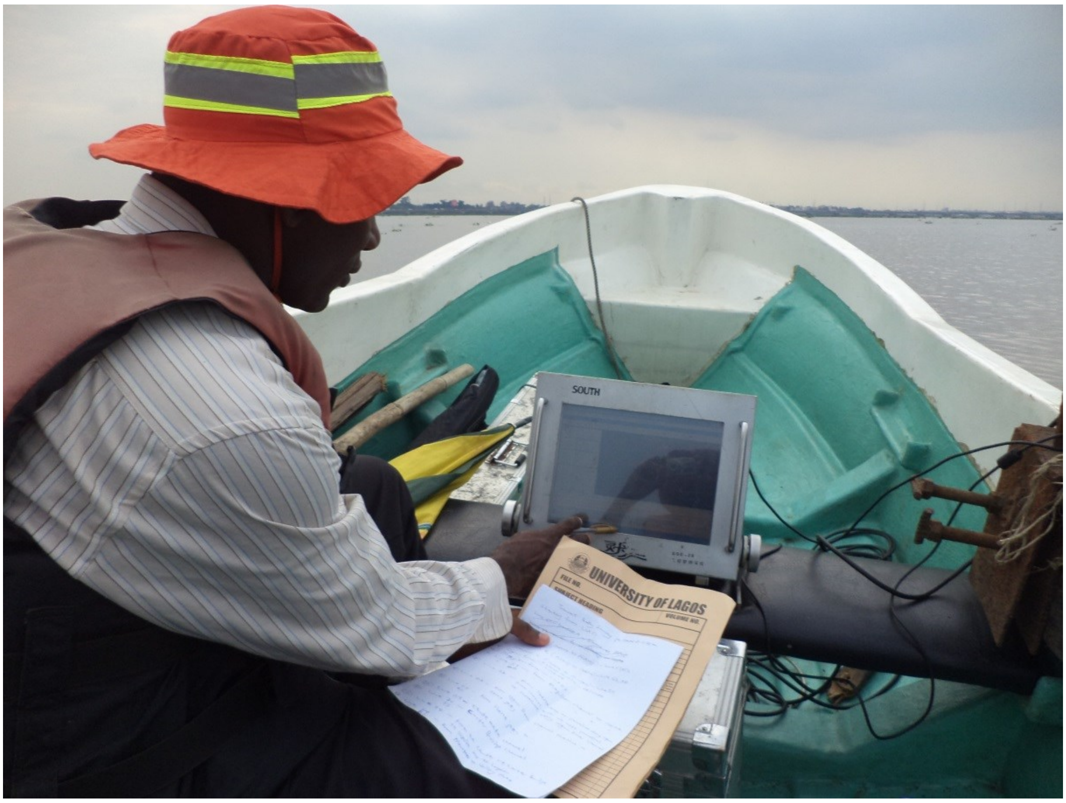


Figure 5.1: Photograph of the survey boat with the single beam echo sounder used for collection of bathymetric data (2014 data) on the Lagoon. The author appeared in the figure taken down some important note

This chapter presents results from repeated bathymetric surveys to measure and monitor the changes in the Lagoon bed due to erosion and accretion. Subsection 5.2 discussed the process of achieving bathymetric survey that produced the data; section 5.3 describes the results of vertical profiles in the area that was covered with acquired data, while section 5.4 focuses on the computation of accretion and erosion geomorphologic units in the part of the Lagoon that was covered during the study. Bathymetric survey was carried out on the Lagoon to cover some section of the lagoon that was easily accessed based on the manpower and logistic available during the research data collection in wet season. The survey covers the western part of the Lagoon through to the near-central region.

5.2 Bathymetric survey

This section presents the procedures utilised for gathering bathymetric data used in the analysis of the Lagoon bed geomorphology. Hydrographic charting has always been of critical concern for navigation; however bathymetric survey charts are often out of date due to geomorphic changes in many submarine areas which most of the time occur rapidly (Gorman *et al.,* 1998), and also lack the detailed resolution required for scientific research level studies. On some navigation chart, it is highly possible that 10 years old bathymetry and the marked depths, all might have changed considerably during the period since the chart was first published. This is especially relevant in the areas of strong current activity, of a mass movement, and where there is strong storm activity, as fast changes could be highly likely. Water depths are measured by both direct contact procedures and by acoustic methods, this research made use of a bathymetric chart that was obtained indirectly with the use of single beam echo sounder. Acoustic depth sounders measure the elapse time an acoustic pulse takes to travel from a generating transducer to the seafloor and back, with the velocity of sound in water known, the travel time of the reflected wave can be measured and converted into distance. With the use of the single beam echo sounder, the section of the of the Lagoon covered in this study was sounded in October 2014 taken note of the reference datum used in the bathymetric survey of the Lagoon in 2008.

5.2.1 Reduction of soundings to chart datum

The depth data acquired was referenced to the local chart datum used in Nigeria (Lagos 1955 height). However, tidal height readings were not measured during the course of the bathymetry survey relative to chart datum at a tidal station (because of security challenge and lack of personnel). Hence predicted tidal values were used to reduce the measured depth to chart datum. The tidal heights are a variation in the sea level that is associated with the gravitational forces maintaining the sun, moon, and the earth in their orbits (Helmuth *et al.,* 2002; Kelaher *et al.,* 2003). The reduction of soundings from floating platforms is traditionally based on the observed tidal time and height at one or more tidal stations and some interpolating techniques together with the associated assumptions to obtain tidal height relative to chart datum at other places.

During the hydrographic survey, the single beam echo sounder on the boat simply measures the depth of the water as the boat moves over the water column. However, the boat as a platform moves vertically depending on the water tide. The Lagoon being in tidal waters, meant the elevation of the water surface in the absence of waves (still water) was measured relative to chart datum. Soundings, relative to chart datum, are simply the surveyed depth less than the height of the vessel relative to chart datum. Water depths that were a reference to known datum were obtained by reducing the sounding depth using predicted tidal values by referencing the water surface to a known on-shore reference benchmark (Unilag 01). Depth was estimated to the best efforts at equipment calibration and data processing, the practicably achievable accuracy for coastal surveys when using echo sounders as ±0.15m (Hilldale & Raff, 2008). The bathymetric data from the field were processed in the office using HYPACK software; this is a package that contains programs for single beam survey design and data collection. A sample of the final data X, Y and Z (depth) coordinates as plotted on the Lagoon is displayed in Figure 5.1 and the sample data in Table 4.1; this is also represented in Table 5.1. The number in the chart is the reduced depth value plotted against its corresponding X and Y coordinates.

Sample of charted depth on Lagos Lagoon

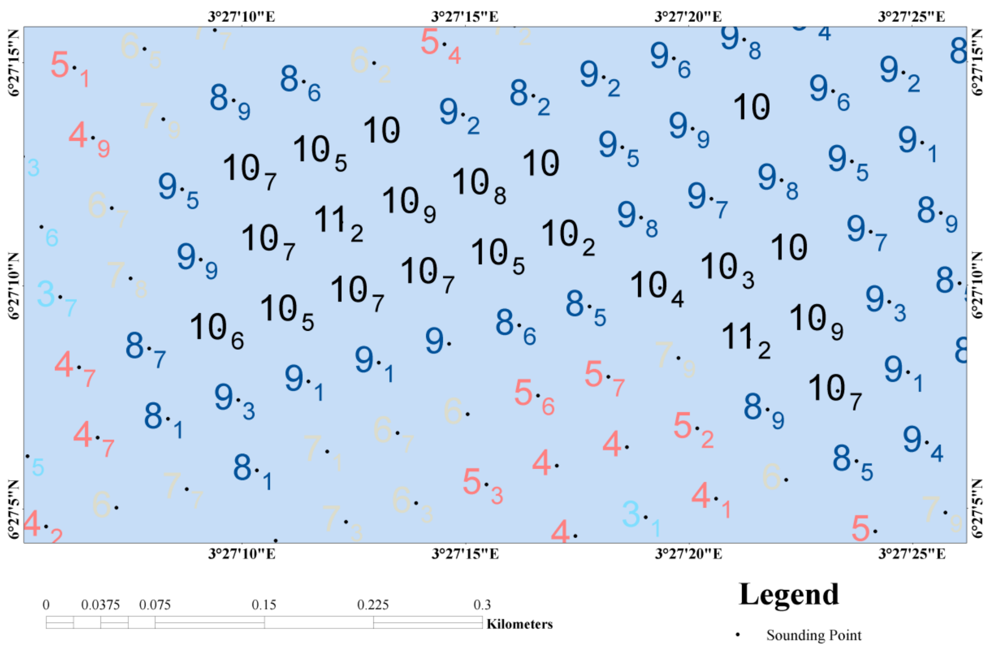


Figure 5.2: Sample of charted bathymetric data of 2014 dry season, plotted in decimal number

Table 5.1: Sample of sounding data after reduction and applied correction

X (m)	Y (m)	Z or depth (m)
544673.4	711969.8	4.3
544771.2	711991	3.93
544847.7	712109.9	5.81
544868.9	712012.2	4.22
544890.1	711914.5	3.42
544945.4	712131.1	5.66
544966.6	712033.4	4.54
544987.8	711935.7	3.85
545043.2	712152.3	6.49
545064.3	712054.6	4.83
545085.5	711956.8	4.25
545106.7	711859.1	3.3
545140.9	712173.5	7.37

5.2.2 Error in bathymetric survey (sounding)

Errors in depth determination using acoustic instruments are caused by physical and mechanical factors, such factors could include the velocity of sound in water and waves. The velocity of sound (V) in near-surface water ranges from 1,400 to 1,525m/sec but varies with water density which is a function of temperature, salinity and suspended sediments (USACoE, 1994; Kuwahara, 1938). Hence change in salinity can change the velocity of the water, due to this the echo sounder was calibrated onsite frequently using bar check. This check was also necessary for boat specific corrections because as the survey progressed, the vessel's draft changes as loads are exchanged (reduced). Wave error which occurs as a result of the survey vessel pitching up and down, in order to obtain true water floor depth, the transducer was installed on the heavy-compensated mount. This allows the boat to move while the instruments remain fixed.

5.3 Analysis of the Lagoon bed dynamics

Profile analysis was carried out on the bathymetric data of 2008 and 2014 from the Lagoon which were plotted in ArcGIS software by creating ten profile sections (Figure

5.3) at distance interval of 100 metres along the coverage area on the Lagoon (Profile lines A-A', B-B', C-C', D-D', E-E', F-F', G-G', H-H', I-I', J-J'). This analysis was performed in order to reveal the variability in the Lagoon bed elevation patterns and volume change that occur along the profile lines. This method was used by (Stauble *et al.,* 1993) for analysis of beach fill profile, where the result reveals clearly regions of erosion and accretion.

The bathymetric Charts (2008 and 2014) were used to depict the changes along each of the profile lines to quantify whether erosion or accretion occurs at a particular location on the Lagoon bed. Over the six-year period, the changes in the Lagoon depth were examined and discussed in the subsequent sections.

The detailed comprehensive results in this section are given in two different segments as comparative results of the profiles running through a west-east direction and a south-north direction on the Lagoon. This made use of the depth datasets for the repeated bathymetry of 2008 and 2014.

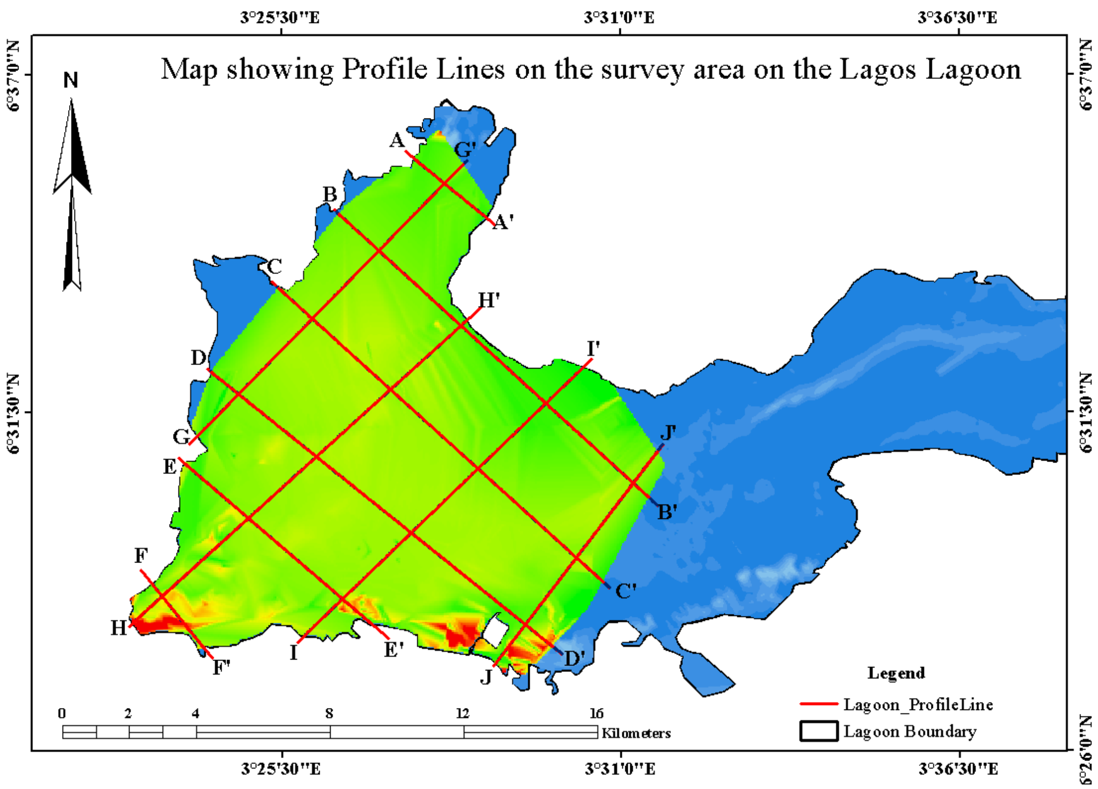


Figure 5.3: Lagos Lagoon with profile lines on the study area. The area on the map with colour blue indicates area covered by the bathymetric survey of 2008 while the area with greenish yellow colour shows area surveyed in 2014

5.3.1 West to East Profiles

Detailed analyses were performed on transects that were created by considering west to east direction to indicate changes along the north – south direction on the Lagoon bed. The essence of creating the west to east direction profile lines is to ascertain the trend of changes on the Lagoon bed moving southward from the freshwater inlets in the north where major sediments from upland intrude into the Lagoon. Thus this analysis determines if there is a significant variation on each of the profile lines on 2008 and 2014 data moving from the north to the south. Therefore, the hypothesis is set as follows to examine if there are significant changes in the Lagoon water bed topography:

1. H_0: There is no significant difference between the 2008 bathymetric data sample and that of 2014 bathymetric data sample in predicting changes in the Lagoon bed.
2. H_1: There is significant difference in the 2008 bathymetric data sample and that of 2014 bathymetric data.

In testing the hypothesis, this study carried out the t-test to test the significant variation of the depth variables of the two repeated bathymetric data which produced the result of the changes on the Lagoon water bed between 2008 and 2014 for the section the Lagoon this study focused on. The t-test compares the actual difference between the means of the two samples depth of 2008 data and the depth of 2014 data. It constructs confidence intervals or bounds for each mean and for the difference between the means. Of particular interest is the confidence interval for the ratio of the variances that extend between particular ranges of value, the results show from the Table 5.3 the profile lines with a significant difference between the means of the two samples at the 95% confidence level not containing the value zero (0).

The first step in this analysis is to present (Table 5.2) extent of changes on the Lagoon water bed that is represented by the change on the two repeated datasets on each of the profiles depth variables on the Lagoon (Figures 5.4-5.9). Erosion which may be principal because of dredging was very prominent at the end of profiles D-D' and F-F' (Figures 5.7 and 5.9). The proving evidence that dredging is taken place at the far end of profile D-D' is the huge sand fill area appearing white on the map in Figure 5.3. However, accretion was the common phenomenon at the end of profiles A-A', B-B', C-C' and E-E' (Figures 5.4, 5.5, 5.6 and 5.8).

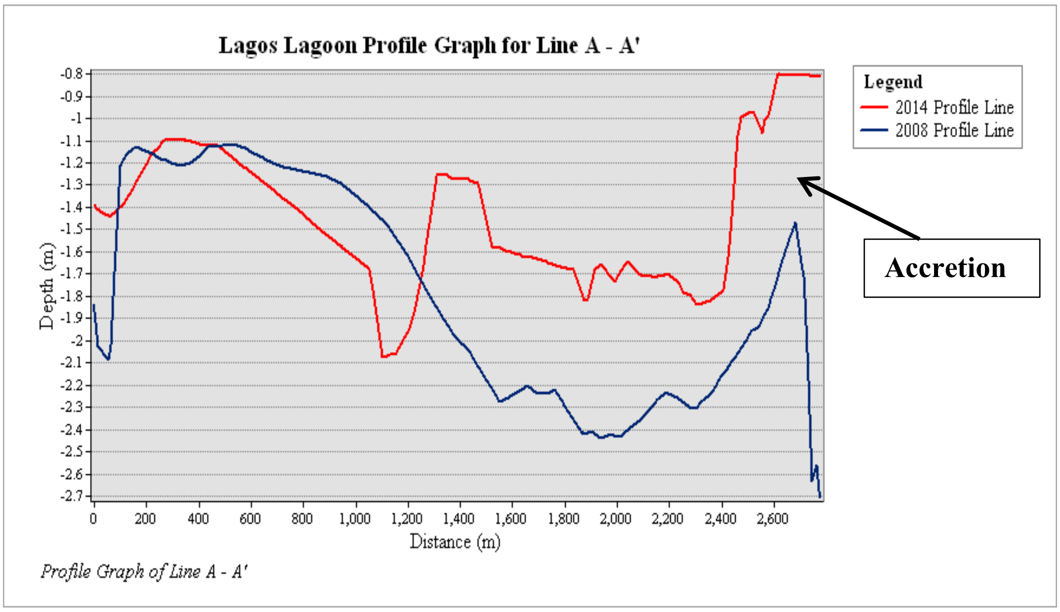


Figure 5.4: Profile section A – A' showing trend of variation in the repeated bathymetric data

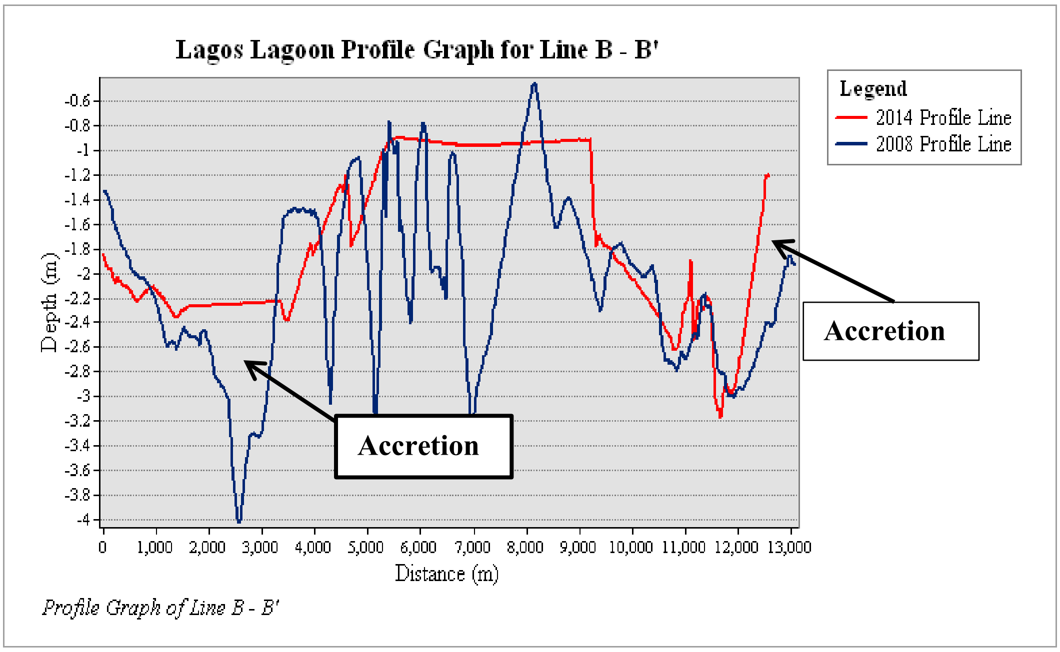


Figure 5.5: Profile section B – B' showing trend of variation in the repeated bathymetric data

Movement of shoals (submerge ridge of sand and unconsolidated materials rising from the bed of the Lagoon to near water surface - Figure 5.6) was exhibited around and along the transect C-C'. This implies that navigation could be very dangerous for boat with draft above 1.4m along the corridor of this transect. However, along transect D-D' and E-E' there was infill somewhere along the mid-way of each transects. The depth of the infill in each transects (approximately 2.3m) implies fast sediment accretion inside the Lagoon and fast erosion of sediment from the Lagoon ecosystem basin. Transect D-D' begins from somewhere closer to Ogudu channel and ends near Five Cowrie channel. It could be observed from Figure 5.7 that channel lateral migration (the geomorphological process that involves the lateral migration of sediment across floodplain. This process is mainly driven by the combination of bank erosion of and bank deposition over time. Hence, channels change is driven by sediment transport) occurred at the end of transect D-D' toward Five Cowrie channel. Comparing this result with existing literature (Brummer *et al.,* 2006; Nanson & Hickin, 1986; Shields Jr *et al.,* 2000) it could be confirmed that lateral migration that occurred at this region which is as a result of the Lagoon bank erosion and sedimentation depends upon the ecology of the watershed corridors of Lagoon ecosystem. Hence, the volume of sediment eroded from the watershed corridors is shown to be largely a function watershed size and grain size of sediment at the base of the outer bank. Consequently, it appears that bank erosion and channel migration are basically problems of sediment entrainment which is dependent on total flow from the watershed and sediment size.

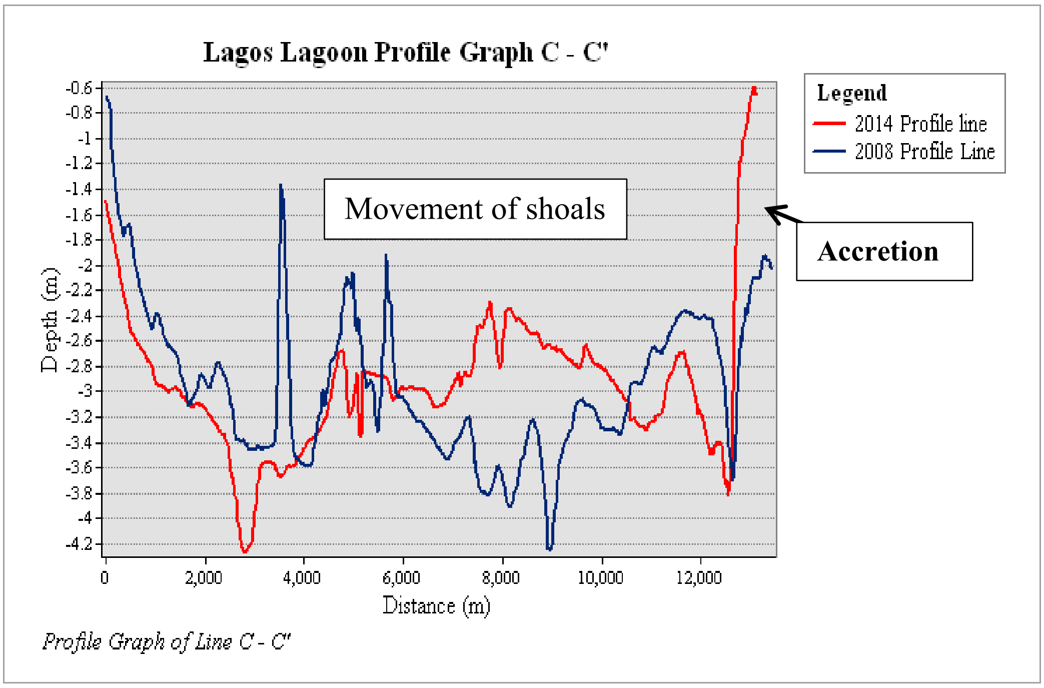


Figure 5.6: Profile section C – C' showing trend of variation in the repeated bathymetric data

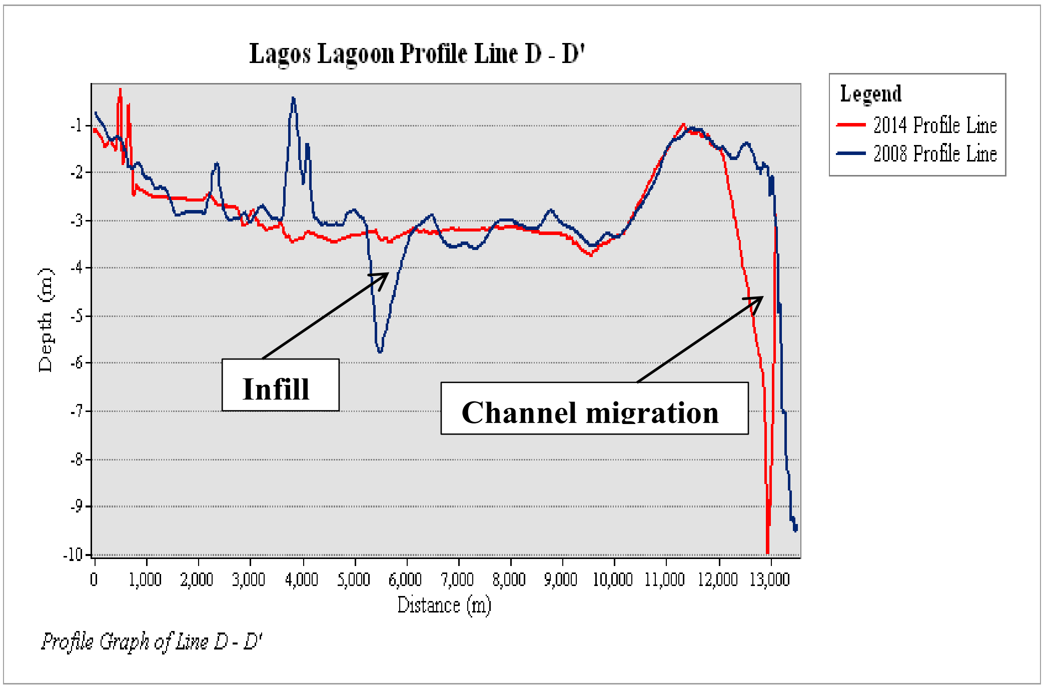


Figure 5.7: Profile section D – D' showing trend of variation in the repeated bathymetric data

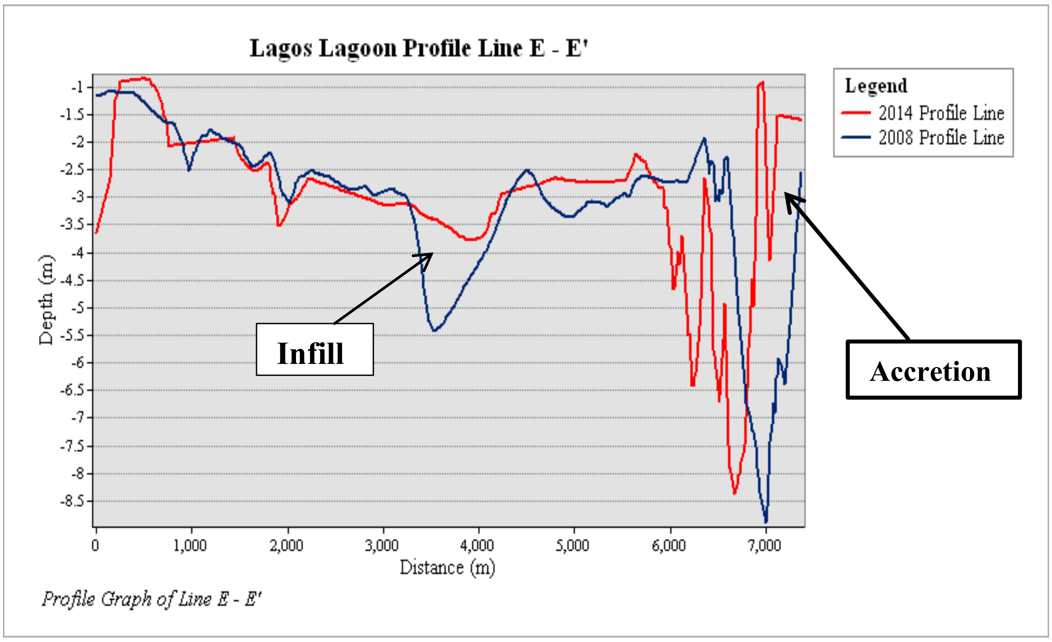


Figure 5.8: Profile section E – E' showing trend of variation in the repeated bathymetric data

Transect F – F' was characterised by channel movement (which in this case is the up and down meandering of the Lagoon bottom morphology), the channel migration by erosion on one side leads to deposition towards the Lagos Island side of the transect, however toward the end of the transect there was dredging. This was confirmed by visual observation during data collection, some local dredging was going on in the area by those who are constructing near the Lagoon bank.

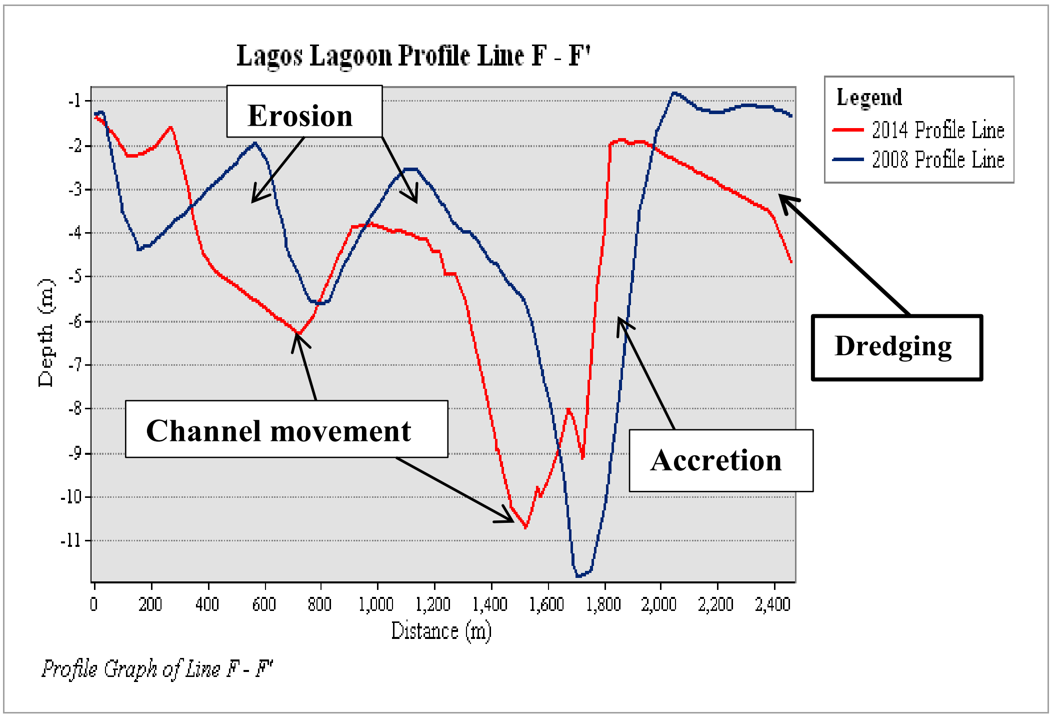


Figure 5.9: Profile section F – F' showing trend of variation in the repeated bathymetric data

In testing the hypothesis, a t-test was conducted to compare the mean values of depths of the two sample data (2008 and 2014 data). The result of the test, that is, the calculated t-test is in Table 5.2. The tabulated values of t-statistics, p-value and confidence interval were calculated for each of the profiles established on the coverage area of the Lagoon at 95% confidence level, which is the probability of making a correct assertion.

Table 5.2: t-test for 2008 bathymetric data against 2014 data for all the transect lines along west – east direction

Profile	t-statistic	p-value
Profile A-A'	-3.62781	0.00061912*
Profile B-B'	-1.08967	0.281534
Profile C-C'	-0.0174967	0.986164
Profile D-D'	1.95931	0.060101

Profile E-E'	-0.180016	0.857449
Profile F-F'	1.02115	0.314395

* denotes a statistically significant difference

5.3.2 Decision on the hypothesis

The six profiles considered along with the direction west to east have different calculated t-values (measure the size of the difference relative to the variation in sample data) and p-values (calculated probability) even though they were all computed with the same confidence interval, this may be evident that the changes along each profile section are not the same. Only Profile line A-A' has a p-value that is less than 0.05, hence the null hypothesis is rejected meaning that there is significant variation in the depth range of the 2008 data and that of 2014. The remaining five profiles have p-value greater than 0.05; it implies that there is no significant difference on the changes along each of the profile line, there could be changes inherent in the profiles which needed a further test to discover it. Hence the null hypothesis is rejected for profile A - A' and conversely accepted for the five profile lines B - B' to F - F'. The implication is that there was significant change along this profile and it is different from the rest of the profiles A to F.

5.3.3 Multiple sample comparison on the west to east direction profiles

Consequent upon the results of the above t-test in section 5.2.1, the six profile sections were further subjected to a robust multiple comparison statistical test. This procedure compares the data in 12 columns of the dataset file. It constructs various statistical tests - F-test, analysis of variance (ANOVA), multiple range tests, and Variance Check (Tables 5.3 – 5.6) to compare the significant changes along each of the profile lines. ANOVA test was used in order to examine and analyse the variance between and within the different profile lines.

The F-test in the ANOVA table (Table 5.3) tests whether there are any significant differences amongst the means. The ANOVA table decomposes the variance of the data into two components: a between-group component and a within-group component. The

F-ratio which in this case equals to 11.08 is a ratio of the between-group estimate to the within-group estimate. Since the p-value of the F-test is less than 0.05 (0.0000); there is a statistically significant difference between the means of the twelve variables of the six profile lines at the 95% confidence level.

Table 5.3: ANOVA Table for multiple sample comparison

Source	***Sum of Squares***	***Df***	***Mean Square***	***F-Ratio***	***P-Value***
Between groups	215.41	11	19.5828	**11.08**	**0.0000***
Within groups	547.811	310	1.76713		
Total (Corr.)	763.222	321			

* denotes a statistically significant difference

To determine which means are significantly different from which others, a Multiple Range Test (multiple comparisons of procedures that use the studentized range statistic to compare sets of means) was performed, the summary results of which are shown in Table 5.3. Out of the 65 paired groups that were tested, an asterisk has been placed next to 35 pairs, indicating that these pairs show statistically significant differences at the 95% confidence level. It can be inferred from this that significant changes occurred on the Lagoon water bed between 2008 to 2014 going from the direction west – east direction of the Lagoon water-bed.

Table 5.4: Multiple Range Test

Contrast	Sig	Difference	+/- Limits
A 2008 - A2014		-0.425517	0.686908
A 2008 - B 2008		0.262744	0.721798
A 2008 - B 2014		0.0548276	0.721798
A 2008 - C 2008	*	**0.890828**	0.831887
A 2008 - C 2014	*	**0.885494**	0.831887
A 2008 - D2008		0.634828	0.831887
A 2008 - D2014	*	**1.37749**	0.831887
A 2008 - E 2008	*	**1.33233**	0.591565
A 2008 - E 2014	*	**1.28283**	0.591565
A 2008 - F 2008	*	**2.01205**	0.784867
A 2008 - F 2014	*	**2.83594**	0.784867
A 2014 - B 2008		0.688261	0.721798
A 2014 - B 2014		0.480345	0.721798
A 2014 - C 2008	*	**1.31634**	0.831887
A 2014 - C 2014	*	**1.31101**	0.831887
A 2014 - D2008	*	**1.06034**	0.831887
A 2014 - D2014	*	**1.80301**	0.831887
A 2014 - E 2008	*	**1.75784**	0.591565
A 2014 - E 2014	*	**1.70834**	0.591565
A 2014 - F 2008	*	**2.43757**	0.784867
A 2014 - F 2014	*	**3.26146**	0.784867
B 2008 - B 2014		-0.207917	0.755078
B 2008 - C 2008		0.628083	0.860921
B 2008 - C 2014		0.62275	0.860921
B 2008 - D 2008		0.372083	0.860921
B 2008 - D 2014	*	**1.11475**	0.860921
B 2008 - E 2008	*	**1.06958**	0.631744
B 2008 - E 2014	*	**1.02008**	0.631744
B 2008 - F 2008	*	**1.74931**	0.815577
B 2008 - F 2014	*	**2.57319**	0.815577
B 2014 - C 2008		0.836	0.860921
B 2014 - C 2014		0.830667	0.860921
B 2014 - D 2008		0.58	0.860921
B 2014 - D 2014	*	**1.32267**	0.860921
B 2014 - E 2008	*	**1.2775**	0.631744
B 2014 - E 2014	*	**1.228**	0.631744
B 2014 - F 2008	*	**1.95722**	0.815577
B 2014 - F 2014	*	**2.78111**	0.815577
C 2008 - C 2014		-0.005333	0.955106
C 2008 - D 2008		-0.256	0.955106
C 2008 - D 2014		0.486667	0.955106
C 2008 - E 2008		0.4415	0.755078
C 2008 - E 2014		0.392	0.755078
C 2008 - F 2008	*	**1.12122**	0.914445
C 2008 - F 2014	*	**1.94511**	0.914445
C 2014 - D 2008		-0.250667	0.955106
C 2014 - D 2014		0.492	0.955106

Contrast	Sig	Difference	+/- Limits
C 2014 - E 2008		0.446833	0.755078
C 2014 - E 2014		0.397333	0.755078
C 2014 - F 2008	*	**1.12656**	0.914445
C 2014 - F 2014	*	**1.95044**	0.914445
D 2008 - D2014		0.742667	0.955106
D 2008 - E 2008		0.6975	0.755078
D 2008 - E 2014		0.648	0.755078
D 2008 - F 2008	*	**1.37722**	0.914445
D 2008 - F 2014	*	**2.20111**	0.914445
D 2014 - E 2008		-0.045166	0.755078
D 2014 - E 2014		-0.094666	0.755078
D 2014 - F 2008		0.634556	0.914445
D 2014 - F 2014	*	**1.45844**	0.914445
E 2008 - E 2014		-0.0495	0.477553
E 2008 - F 2008		0.679722	0.702939
E 2008 - F 2014	*	**1.50361**	0.702939
E 2014 - F 2008	*	**0.729222**	0.702939
E 2014 - F 2014	*	**1.55311**	0.702939
F 2008 - F 2014		0.823889	0.871889

* denotes a statistically significant difference

To further ascertain the change within and between the twelve pairs of profile lines, a variance check test was carried out using Levene's method (Gastwirth *et al.,* 2009). This statistic tests the null hypothesis that the standard deviations within each of the twelve columns are the same. Of a particular interest are the generated p-values. A summary of the statistical test results (Table 5.5 and Table 5.6) shows that there is a statistically significant difference amongst 47 out of 65 paired groups with the standard deviations at the 95% confidence level.

Table 5.5: Variance Check

	Test	P-Value
Levene's	6.69373	**4.51871E-10**

Table 5.6: Summary of the statistical test variance check

Number of paired Profile	Range of P-Value	Significant Status
47	Less than 0.05	Statistically significant
19	Greater than 0.05	Statistically not significant

Table 5.6 shows a comparison of the standard deviations for each pair of samples. P-values less than 0.05, of which there are 47, indicate a statistically significant difference between the two sigmas at95 % significance level.

As part of these analyses, a Least Significant Difference (LSD) assessment was carried out on the twelve pairs using Fisher's LSD; it gives the opportunity to deduce which group is significantly different from another; this is not possible using ANOVA. The LSD calculates the smallest significance between two means as if a test had been run on those two means. It makes direct comparisons between two means from two individual groups and any differences larger than the LSD is considered a significant result. The test takes the square root of the Residual Mean Square from ANOVA and considers that to be the pooled Significant Difference (SD), taking into account the sample sizes of the groups being compared; it computes a standard error of the difference between the means. It also computes a t ratio by dividing the difference between means by the standard error of that difference. The various results exhibited by each groups is displayed in the graph of Figure 5.10. Comparing the results of the Figure 5.10 and the summary results Table 5.6, it can be concluded that significant change exists between 2008 and 2014 on the Lagos Lagoon water bed from the northern region to the southern region of the lagoon.

Finally, of a particular interest is the p-value of profile A-A' at the north most region very close to the inlets, this has a p-value of 6.19×10^{-4} which is less than 0.05. The error bar of the A' transect (2014 transect dataset) does not overlap with all the transect line C to F', so also is transect A. This indicates that a statistically significant difference in the depth values of transect lines AA' and those of C to F'. However, transect CC' shows no difference at all but does show significant variation with transects AA' and FF'. It can be concluded that significant changes have taken place between and within the transect line at varying degrees. Interestingly, it is evident in the results of Figure 5.4 – 5.9 that erosion, shoaling, channel migration, channel movement and accretion take place along a west-east direction at different spatial location.

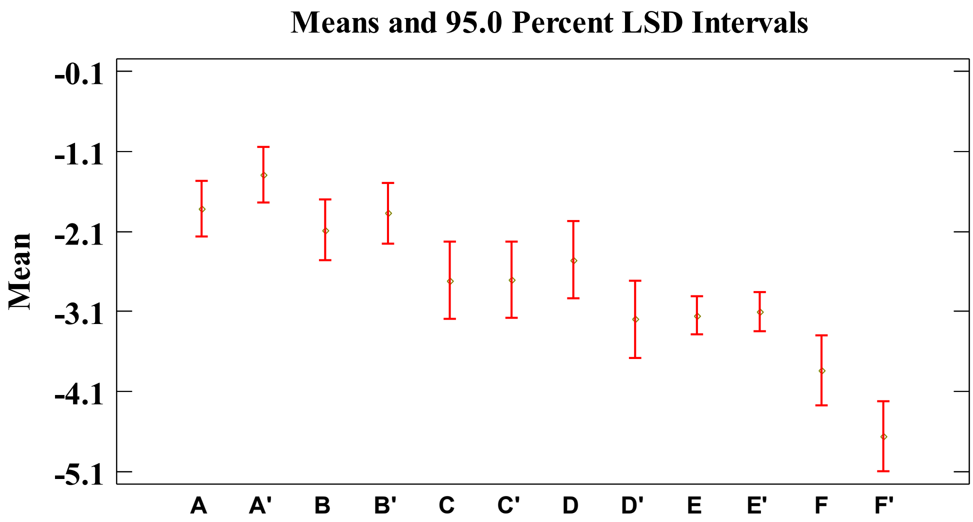


Figure 5.10: Multiple comparisons means plot with 95.0 percent LSD intervals

5.3.4 South to north profiles

Furthermore, four profiles lines (Table 5.7) were created in a longitudinal direction to investigate the changes on the Lagoon along the direction west to east. The choice of this transect lines was based on the fact that human activities and urban development are more pronounced in the western part of the Lagoon than what goes on in the eastern region, hence the reason for investigating the trend of changes on the Lagoon water-bed moving from west to east on its water-bed. Likewise, some places of significant human activities were identified where a possibility for a high erosion and siltation rate on the Lagoon bed could be feasible. A good example of such is the profile HH' (Figure 5.3) constructed from the southwestern region of the Lagoon outlet around Carter Bridge. This region is known for heavy traffic: ferries and other human activities such as local sand mining. The position of profiles I-I' and J-J' were strategically chosen because a lot of dredging activities are going on in the area due to increased urban development and a struggle for space around the Lagoon coast. It was assumed that accretion due to sediment transport from the uplands would be more pronounced in the western part than in the eastern side of the Lagoon; this is assuming there is no dredging activity going on in the Lagoon.

Thus, this analysis investigates if there is a significant change on each of the established profile lines of 2008 and 2014 bathymetric datasets along south/north direction. Therefore, the hypothesis is set as follows:

1. H_0: There is no significant difference between the 2008 bathymetric data sample and that of 2014 bathymetric data sample in predicting changes in the Lagoon bed along the easting direction.
2. H_1: There is significant difference in the 2008 bathymetric data sample and that of 2014 bathymetric data along the easting direction.

In testing the hypothesis in this section, the research carried out a t-test to test the significant variation of the depth variables of the two repeated bathymetric data (2008 and 2014). The test constructs confidence intervals for each mean and for the difference between the means. It also compares the actual difference between the means of the two samples. The analysis presents (Table 5.7) a result of statistically significant differences existing along the profiles and the extent of change along each profile is presented graphically (Figures 5.14 to 5.17) as results from ArcGIS.

From the statistical tests of the four south-north directional profiles, the values of t-statistics and p-value calculated for individual profile section at 95% confidence level. Other statistical tests were performed for further comparison of the individual data files that was involved in constructing each of the profiles. Further tests, F-test, ANOVA, multiple range and variable check, (Tables 5.7 to 5.9) were constructed to further examine the result of the t-test and confirm the scientific evidence of the statistic tests. The F-test in ANOVA table, the statistically significant difference of the data means and the expression of the Multiple Range test shows a p-value of 0.000037848, hence there is a significant difference between the 2008 and 2014 bathymetric data around the region of profile H-H'. Consequent upon the result of the F-test, the procedure of the multiple sample comparison compares 8 columns of data to reveal the overall changes between the two data sets in south-north directions.

5.3.5 Results of the statistical Test

The t-test results for each profile line is summarised in Table 5.7. Line H-H' show a p-value that is less than 0.05, meaning that statistically, there is a significant difference between the depth values of the 2008 and 2014 data. It implies that some significant changes took place on the Lagoon bed either through accretion or erosion around the profile section H-H'.

Table 5.7: South to North Profiles

Profile	t-statistic	p-value
Profile G-G'	0.348271	0.727964
Profile H-H'	4.1955	0.000037848*
Profile I-I'	-1.71216	0.090557
Profile J-J'	1.30189	0.199436

* denotes a statistically significant difference

The fact that the p-values of the other three profile sections (G-G', I-I' and J-J') are greater than 0.05 does not mean there is no change experienced between the gap year of the repeated data. The result of the ANOVA test shows F-ratio as 9.18 (Table 5.8), this is the ratio of the between-group estimate to the within-group estimate. The p-value of the F-test is less than 0.05; this implies that there is a statistical significance between the means of the 8 variables at 95% confidence level. A Multiple Range Test was carried out on the 8 profiles, considering each profile as a variable so as to determine which of the profile depth mean (average) are significantly different from the other (Table 5.9).

Table 5.8: ANOVA Table

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	56.9298	7	8.13284	9.18	**0.0000**
Within groups	534.972	604	0.885715		
Total (Corr.)	591.902	611			

Table 5.9: Multiple Range Test

Contrast	Sig.	Difference	+/-Limits
G 2008 – H 2014	*	**0.782877**	0.238985
G 2014 - H 2014	*	**0.75562**	0.238985
G 2014 - I 2008	*	**0.505063**	0.33051
H 2008 - H 2014	*	**0.614762**	0.232394
H 2014 - J 2008	*	**-0.928135**	0.410819
H2014 - J 2014	*	**-0.603552**	0.410819

* denotes a statistically significant difference

From the table of results on multiple range tests, six contrasts show a result that is significantly different, which implies significant variations in the depth of the 2008 and 2014 data sets. Further confirmation of the change is graphically displayed in Figure 5.11. The difference in the mean of the dataset on line H-H' that was overlaid on each other shows a wide variation. The variations in the mean values of the two datasets on the same profiles are very visible on profiles H-H', I-I' and J-J'. It could be inferred from Figure 5.11 that a mean depth of 3.1m in 2014 against the mean depth of 2.5m in 2008 shows erosion (whether by dredging or naturally) around and along the profile section HH’. On the contrary, accretion (that is sediment gain) was shown from the region of profile H' to profile J. However the ArcGIS model result in Figure 5.12 confirms the region of accretion and erosion on the Lagoon bed within that interval of six years. To put it differently, in a graphical representation, the changes on the Lagoon bed moving in the direction west to east are depicted in figures 5.14 to 5.17**.**

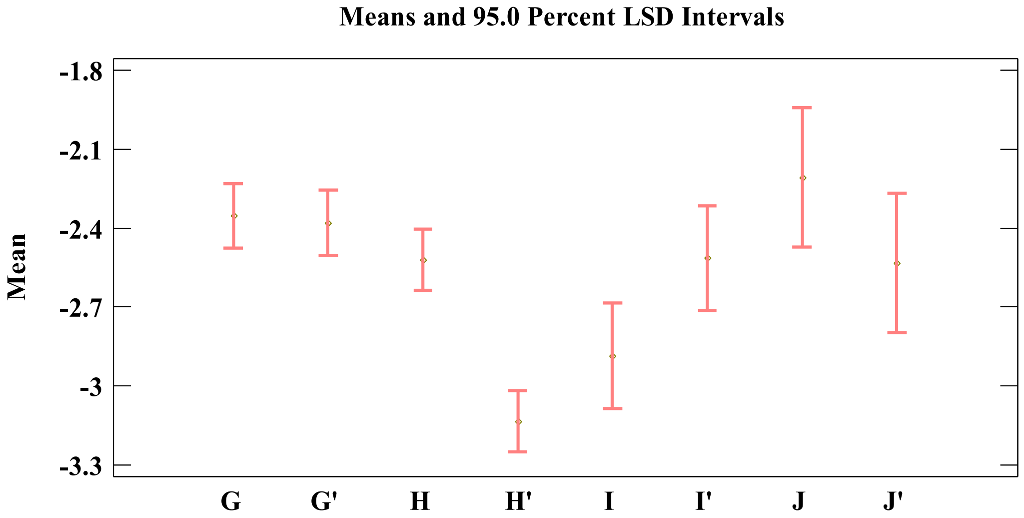


Figure 5.11: Multiple comparisons mean plot with 95.0 percent LSD intervals for south-north direction profile

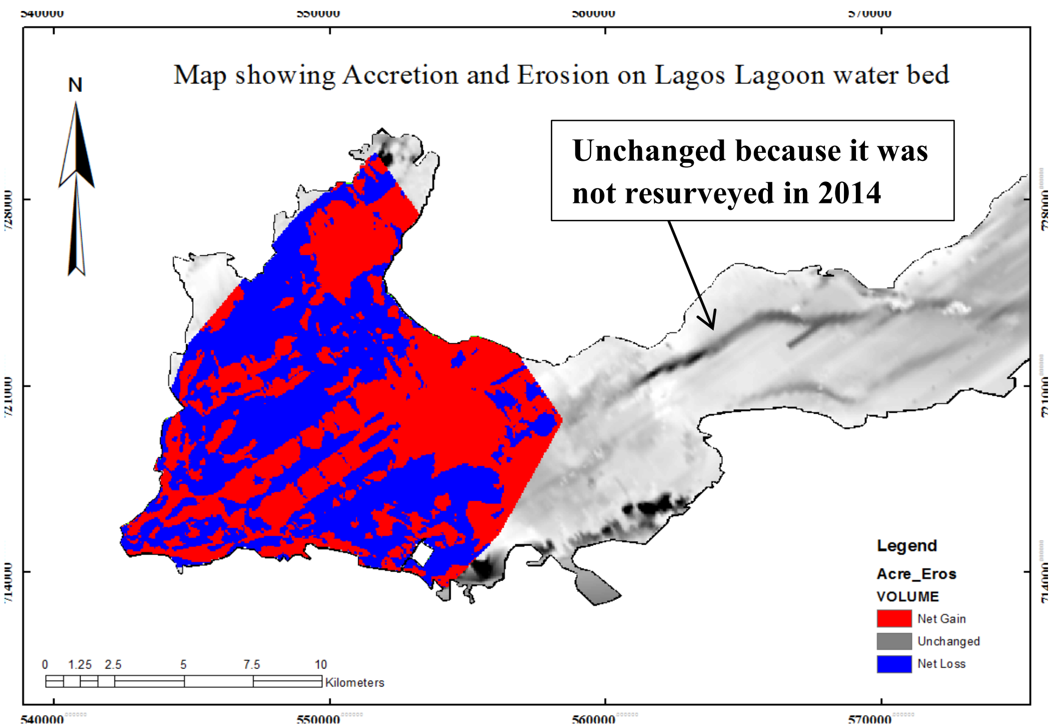


Figure 5.12: Accretion and erosion on Lagos Lagoon water bed between 2008 and 2014. Accretion is shown in red as sediment net gain while erosion is in blue colour as sediment net loss.

5.4 Overall test on the Lagoon spatial depth characterisation

Further to the statistical test carried out on west-east and south-north directional profiles, the differences in the depths of 2008 and 2014 data were extracted and arranged profile by profile. An ANOVA test with a posteriori comparison (Table 5.10) was carried out on the depth differences. The ANOVA decomposes the variances of all the datasets into two components: a between-group and a within-group component. A high value of F-Ratio (5.00) with p-value 0.00, therefore, is evidence against the null hypothesis that was originally set as equality of all the profile data set population means. Hence there is a statistically significant difference in the Lagoon bed between 2008 and 2014 derived from the repeated bathymetric surveys. The analysis of means plot with 95% decision limits revealing a high level of significant difference in profiles H-H' and I-I'. These were the two profiles that exceeded decision limits (Figure 5.13) that were set as 95% decision limits at both upper and lower limit of the mean.

Table 5.10: ANOVA with a posterior test

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
Between groups	70.1009	9	7.78898	**5.00**	**0.0000**
Within groups	711.974	457	1.55793		
Total (Corr.)	782.075	466			

It can be inferred from the results of the test that around the region of profiles H-H' and I-I' significant changes took place on the Lagoon bed. Correlating the region between profile H-H' and profile I-I' with the erosion/ accretion result in Figure 5.12, a high level of erosion or loss of sediment has taken place in the area which is shown as a net loss in Figure 5.12.

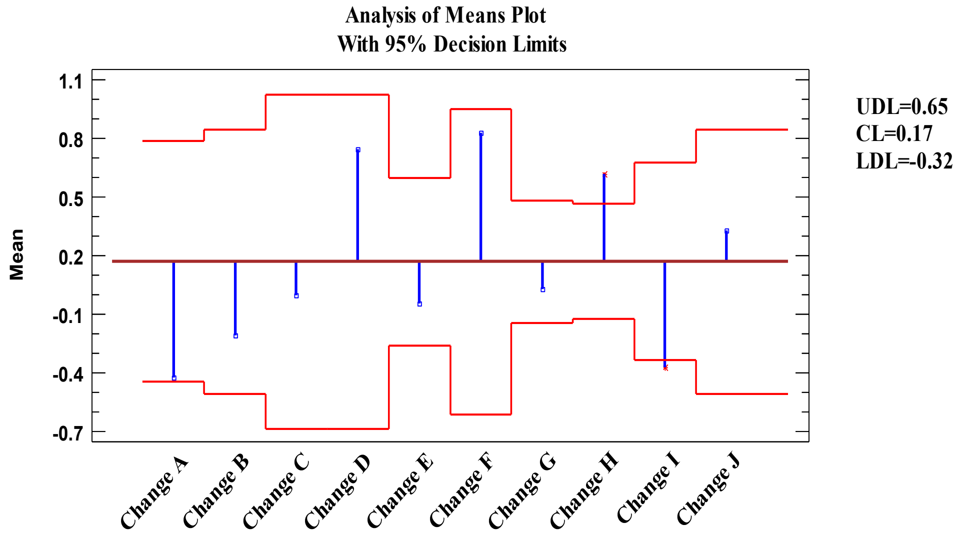


Figure 5.13: Analysis of Mean for all change in depths from profile A-A' to J-J'

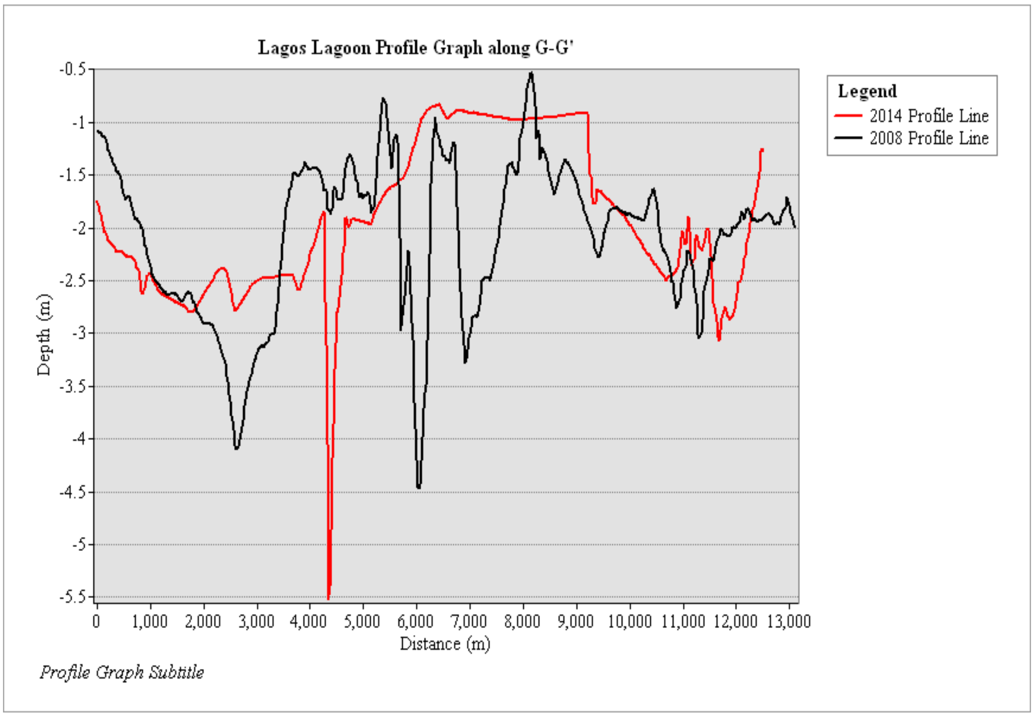


Figure 5.14: Profile section G – G' showing degree of variation in the depths of the Lagoon repeated bathymetric data

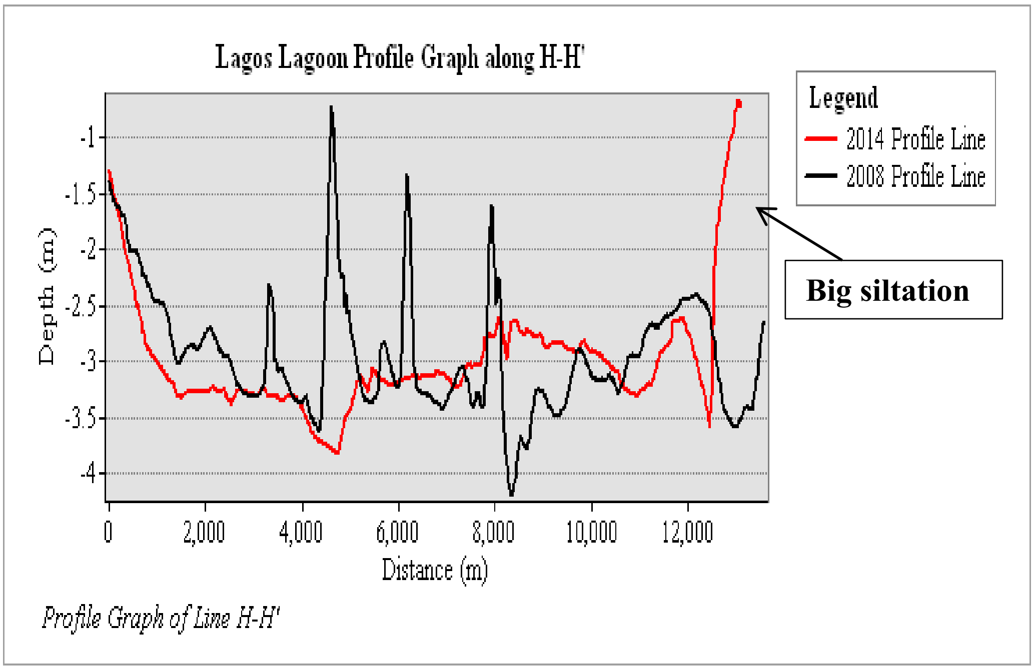


Figure 5.15: Profile section H – H' showing degree of variation in the depths of the Lagoon repeated bathymetric data

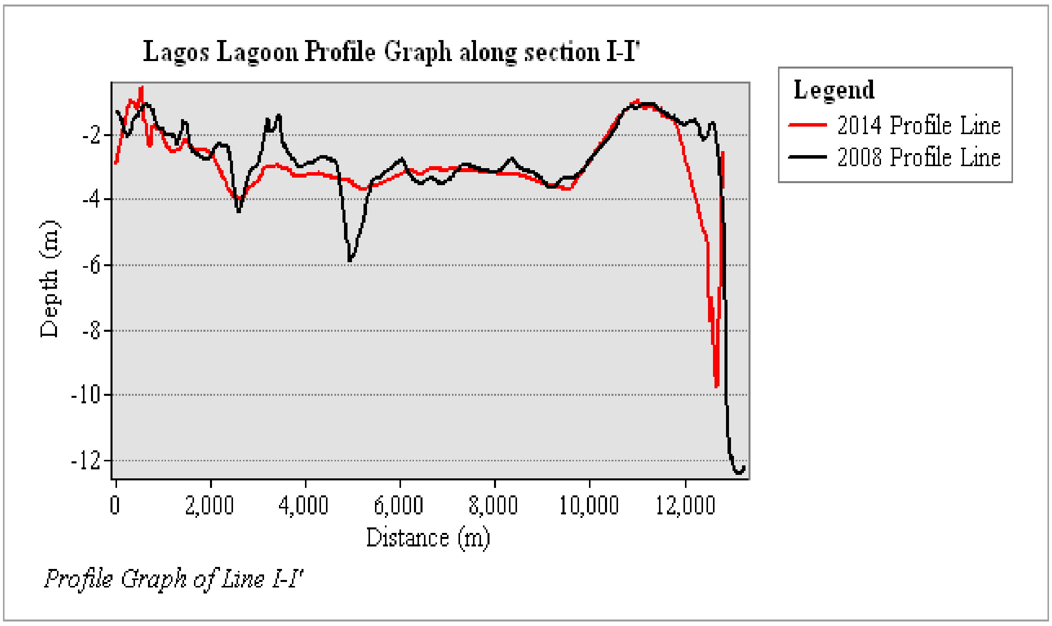


Figure 5.16: Profile section H – H' showing degree of variation in the depths of the Lagoon repeated bathymetric data

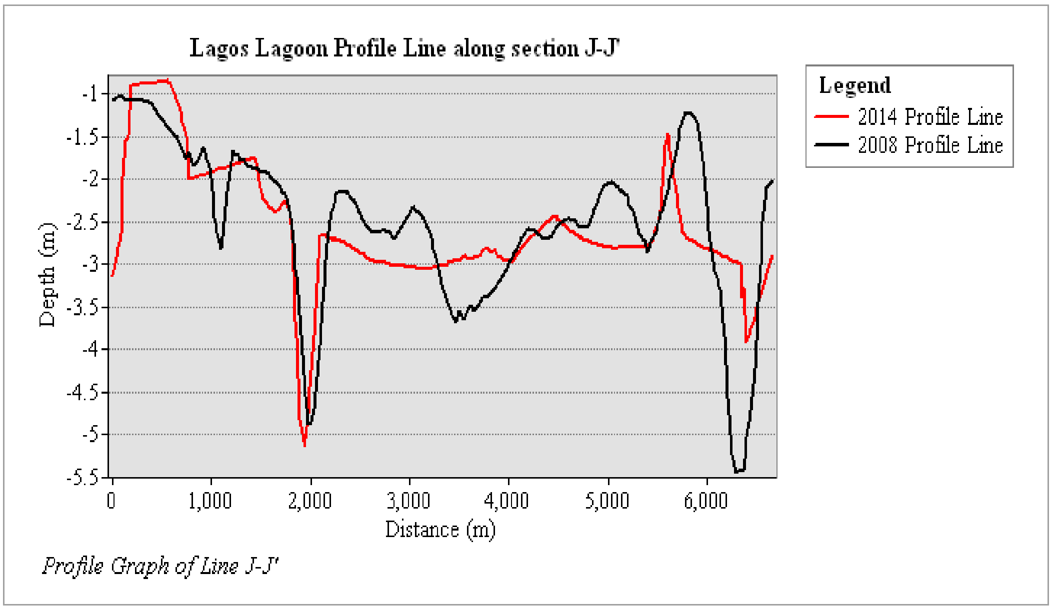


Figure 5.17: Profile section H – H' showing degree of variation in the depths of the Lagoon repeated bathymetric data

5.5 Volume Analysis

Volume estimates were calculated using CUTFILL tool in ArcGIS's 3D Analyst. The uncertainty inherent in the volume estimation using CUTFILL tool is computed in terms of percentage deviation (±5%). The depth values of the two repeated bathymetric datasets from 2008 and 2014 were used to determine how much sediment has been accumulated or eroded on any part of the Lagoon water bed. The two dataset (2008 and 2014 bathymetric data) were plotted on ArcGIS and then converted to shapefiles, next was the conversion of the shapefile to vector-based digital geographic data using Triangular Irregular Network (TIN) in order to make it a surface morphology. A TIN is a vector data structure that stores and displays surface models; it partitions geographic space using a set of irregularly spaced data points, each of which has x, y, and z values. These points are connected by edges that form contiguous, non-overlapping triangles and create a continuous surface that represents the terrain.

The CUTFILL tool in the ArcGIS environment was used to identify the areas where dredging/erosion and deposition/accretion have taken place in the study area on the Lagoon (Figure 5.12).

5.6 Calculation of volume gained

The single beam hydrographic data of 2008 and 2014 have been used to determine the degree of changes that has taken place for the six year period. Hence the amount of sediment eroded or gained was calculated using the depth range from the datasets created on Triangular Irregular Network (TIN). The TIN morphological surface was converted to raster data and was used in the CUTFILL tool to determine the volume gain or loss. To analyse the change in the sediment volume between 2008 and 2014, a statistical summary from the ArcGIS model was used. A summary of the gain/loss analysis is depicted in Table 5.11. The amount of accretion was found to be higher than that of erosion/dredging on the Lagoon water bed despite all the local sand extraction going on consistently in the Lagoon.

It can be inferred from the Table that 858932m^2 on the Lagoon gained 137429m^{3}volume of sediment between 2008 and 2014. Hence, the depth of accreted sediment over the area was computed as:

Volume = Area*height

137,429.161 =858,932.254*height

Hence sediment gained = 137,429.161/858,932.254

Average height of sediment gained = 0.16m

Between 6 years, the average height of 0.16m was gained by the Lagoon. Going by this rate it means that in 1 year the height of accretion will be 0.026m.

Table 5.11: Summary of erosion/accretion calculation on the Lagoon water bed

Sediment Status	Volume (m^3)	Area (m^2)
Accretion	54,148,636	70,944,744
Erosion	54,011,207	70,085,812
Total Accretion or Erosion	137,429	858,932

5.6.1 Evidence base

If the yearly average accretion (0.026 m/year) persists in the Lagoon without any dredging/other removal, the study area of the Lagoon will have gained a sediment height of 1.3m in 50 years. Kjerfve & Magill (1989) confirm that lagoons are net material sinks and that they are often subject to rapid sedimentation and will transform into other types of environments through sediment infilling and land-use activities. Hence its time scale of transition since it is geologically rapid can occur within decades to centuries, and the Lagos Lagoon, as is the case with any other lagoon, is susceptible to disappearing after some decades. Kjerfve & Magill (1989) use a systematic review approach and concluded that lagoons will quickly transform into other types of coastal environment without using any data to substantiate their inference. However, this aspect of the research has been able to confirm with scientific evidence that the Lagos Lagoon is a net material sinks, subject to rapid sedimentation and can easily transform or go into extinction.

The spatial variability of erosion and accretion on the Lagoon bed (Figures 5.18 and 5.19) shows that a large area of about 70,944,744 m^2 was submerged into accretion with approximately 54,148,636 m^3 volume of sediment gained around the area. This large sediment deposition gives an indication that change in the Lagoon bed is evident that sediment is drifting constantly into the Lagoon through erosion reducing the depth of the Lagoon very fast despite the fact that there are local dredging going on the system.

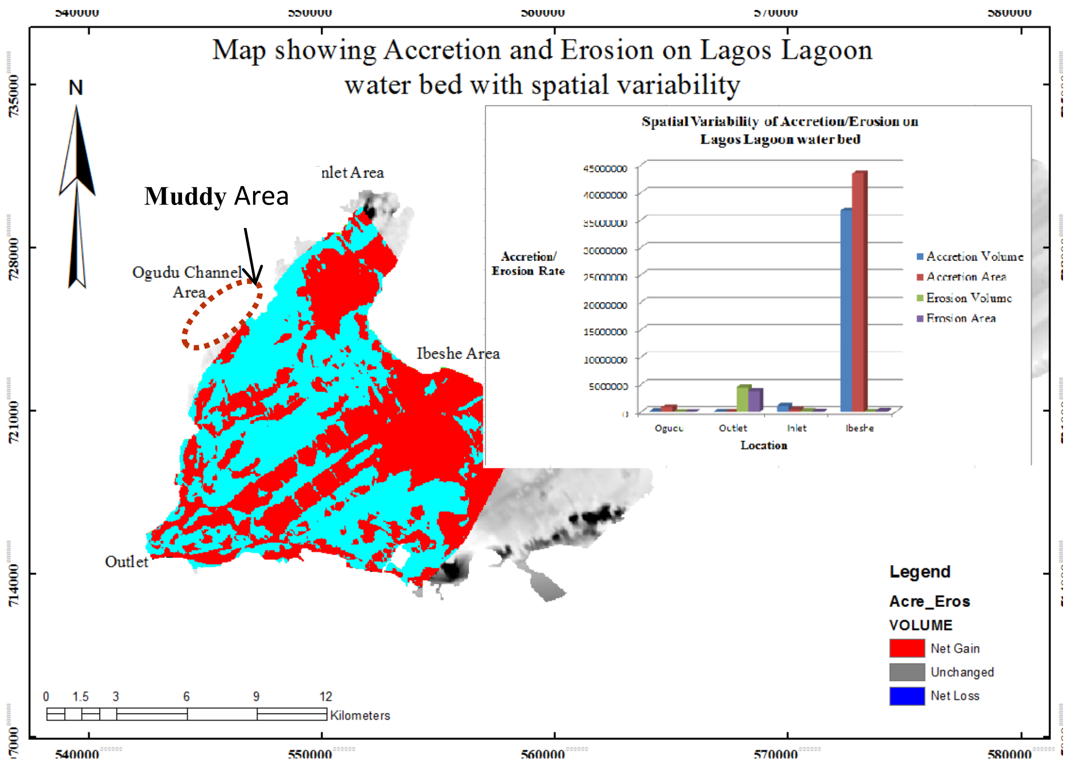


Figure 5.18: Spatial variability of sediment Accretion and Erosion on Lagos Lagoon water based on 2008 and 2014 repeated bathymetric data

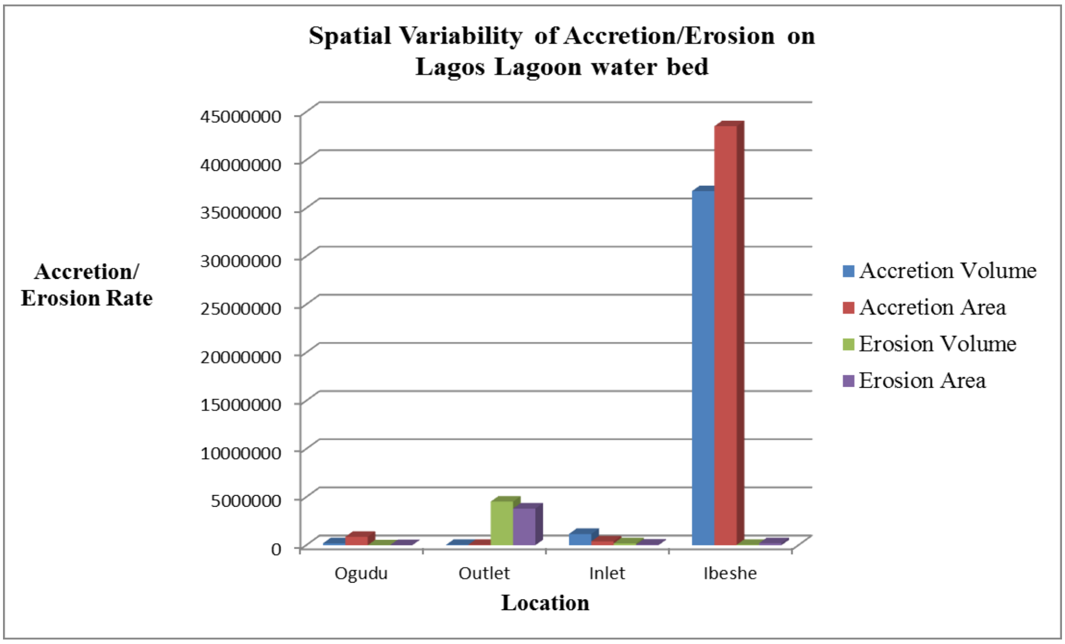


Figure 5.19: Chart showing spatial variability of sediment accretion and erosion on Lagos Lagoon bed based on two repeated bathymetric data of 2008 and 2014

5.6.2 The region west of the Lagoon: Sediment migration around Ogudu Region

The Ogudu inlet area shows a complicated bed pattern, which potentially endangers small boat movement because of its extremely shallow depth possibly due to the influx of industrial effluents and sediments that have been channelled through the place.

It was impossible to take measurements around the Ogudu region of the Lagoon during the research field data collection; possibly it could be inferred from the result in section 5.6 that a fast accretion of sediment takes place in the western zone of the Lagoon where there is a large human population, and industrial settlements are located. This region is where the Ogudu channel brings the largest quantity of sediment into the Lagoon.

Generally, the mean difference of the depth value of 2008 and 2014 dataset was found to be extremely small. This was shown in the multiple range tests in Table 5.4 as approximately -0.251, the mean difference of profile C of 2014 and profile D of 2008. This implies that whatever the depths range from the area of this region of the Lagoon in 2008 it has been reduced excessively in 2014. The decrease in the depth of the Lagoon water bed could likely be increasing as a result of urbanisation that has exposed the majority of the Lagoon ecosystem which invariably cause increase erosion of sediment to the Lagoon.

5.6.3 Significance of the accretion spatial variability

Four locations near to urban growth were chosen to take Lagoon bed samples. Very significant to the sediments from each of the locations is that their grain sizes are very similar both in colour and texture, Tables 5.12 (i-iv) show the summary of the sieve analysis performed on the sediments collected from the four locations. The results show the composition of the whitish shell as a major boulder or cobble sediments in three of the locations, this could imply that the effect of increase stress (through human activities) on the Lagoon ecosystem where the habitats live, hence their displacement probably leads to their extinction as their habitation is depleted. The sediments around Ebute-Meta show large grain size than any other locations. This could likely be sediments of industrial refuse that are channelled into the Lagoon through Ebute-Meta channel where the sample was collected.

At Ijede, the grain with the largest percentage of sediment during sieve analysis was silt and sand, hence the prevailing colours were mostly brown (silt sediment) and grey (sand sediment). The texture of the sample at this location was slightly cohesive and frictional. However, the sample at Ebute-Meta was slightly different from that of ijede in that there is more cobbles sediment at Ebute-Meta than the proportion present in Ijede. The sample at the inlet completely displays sediment that is largely cohesive clay, dark brownish in colour, but completely void of cobble-sized sediments from the remains of water snail shells.

Table 5.12: Sieve analysis of sediment from four spatial locations around the Lagoon

(i) Five Cowries

Size of mesh (mm)	**Sediment weight (g)**	**Remark**
2.36	2.5	100% Whitish brown shell
1.18	1.8	Whitish brown
600μm	3.1	Whitish brown
425 μm	3.6	
300 μm	10.4	
212 μm	29.0	
150 μm	24.0	
75 μm	23.7	

(ii) Ebute-Meta

Size of mesh (mm)	Sediment weight (g)	Remark
2.36	8.22	90% Whitish shell
1.18	6.07	White shell and 60% brownish grains
600µm	12.05	Brownish grains
425 µm	4.97	
300 µm	5.64	Dark and brownish grains
212 µm	10.79	Dark and brownish grains
150 µm	12.95	Dark and brownish grains
75 µm	21.08	

(iii) Ijede

Size of mesh (mm)	Sediment weight (g)	Remark
2.36	1.7	100% whitish shell
1.18	1.63	60% brown pebbles
600µm	20.46	99% brown pebbles with traces of whitish grains
425 µm	14.27	Grains with black patches
300 µm	16.44	Grains with black patches
212 µm	21.85	Brown with dark grains
150 µm	13.26	Brown with dark grains
75 µm	7.66	Darkish brown grains

(iv) Inlet

Size of mesh (mm)	Sediment weight (g)	Remark
2.36	0	
1.18	0.12	Blackish grains
600µm	1.28	Blackish grains
425 µm	0.63	Blackish grains
300 µm	0.78	Blackish grains + whitish patches
212 µm	1.00	Blackish grains + whitish patches
150 µm	1.19	Blackish grains with shinning whitish grains
75 µm	26.26	Dark brownish with whitish grains

Further analysis was carried out on quantitative verification of the sediment gain in some part of the Lagoon bed using the initial four spatial locations. The volume of sediment accreted in the area was calculated with the coverage area. To establish the relationship that exists between the volume of sediment and area covered, an analysis of variance (ANOVA) was carried out to test whether there is significant difference between the volume of sediment and the area (with 95% confident interval). The result of the ANOVA test is summarised in Table 5.13 which shows that there is a significant difference in the volume of sediment accretion/erosion in the area subject to the test.

Table 5.13: ANOVA test on change in sediment deposition in six spatial locations on the Lagoon

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1.11515E15	1	1.11515E15	2446.67	**0.0000**
Residual	2.27891E12	5	4.55782E11		
Total (Corr.)	1.11743E15	6			

Summary of the Analysis of Variance

Correlation Coefficient = **0.99898**

R-squared = **99.7961** percent

R-squared (adjusted for d.f.) = **99.7553** percent

Standard Error of Est. = **675116.**

Mean absolute error = **477716.**

5.7 Error analysis

This section outlines the basic procedure that is used for calculating volumetric errors provided the estimates of the vertical (Δd) are known. If Δd values are unavailable for the specific surveys, standard errors of ±0.15m, ±0.3m or ±0.45m can be used based on the class of survey (Gorman et al., 1998). For every coastal survey (surveys on lagoons, estuaries, lake and surveys close to the shore), it is assumed that errors in horizontal positioning (Δx and Δy) are random and have an insignificant effect on the volumes compared with possible errors in water depth measurements, tide correction and data reduction.

The volumetric error difference between different repeated bathymetric surveys was estimated by determining how much the average depth in each chart changes from one survey to another. Maximum likely error (MLE) was computed as:

$$MLE = \frac{2 \times \Delta z}{\Delta z_{ave}} \qquad 5.1$$

Where Δz is change in depth between the different surveys at a point

Δz_{ave} is average of depth changes over the entire survey area

Three points were sampled at approximately mid-region on the area where bathymetric data was collected on the Lagoon, depth difference between the two repeated bathymetric data was determined, averaged and recorded as Δz. Δz_{ave} was determined by taken difference in the depth between the two bathy data at difference part of the data coverage to ensure this is distributed almost equally over the data coverage, the mean is taken and recorded as average of depth changes over the entire survey area. The values of the two variables were computed as:

$\Delta z = 0.27$

$\Delta z_{ave} = 1.211$

Therefore $MLE = \frac{2 \times \Delta z}{\Delta z_{ave}}$

$$= \frac{2 \times 0.27}{1.211}$$

= 0.446, approximately 45 percent

This means that the maximum likely possible error from the two repeated bathymetric data is 45 percent. The lesser the percentage the better the surveys and the better the specifications used in the surveys (Gorman *et al.,* 1998). The computed percentage is allowable for engineers' survey in the coastal area (Gorman *et al.,* 1998). Hence for monitoring purpose the maximum likely error MLE is suitable to detect changes on the Lagoon bed.

5.8 Accounting for Uncertainty in the Lagoon bed dynamics

Depth plays a significant role in the monitoring of the Lagoon bed dynamics because depth measurement is a key parameter that influences many processes involved in Lagoon changes as is the case in coastal change (Gesch, 2009). This section of the study has produced maps and statistical summaries of the potential risk of losing the Lagoon to sediment accretion and that it could be filled up with sand in a few decades.

Limitations of the monitoring assessment using repeated hydrographic surveys to serve as the uncertainties, which includes the disturbances produced by small vessels and the uncontrolled human activities on the water which cannot easily be accounted for. For this study, the uncertainty in the monitoring assessment was not accounted for because of the short time that was allotted for data gathering and unavailability of personnel that affect the accuracy of the bathymetric data, that is, the local sand mining.

From the four spatial locations selected for comparative analysis of erosion and accretion variability on the Lagoon bed floor (Figure 5.18), three of the locations (Ibeshe, Inlet and Ogudu) show that the areas are prone to accretion more than erosion. Ibeshe area (northeastern) of the Lagoon recorded the highest rate of sediment accretion. In contrast, the Lagoon outlet area exhibits more erosion than accretion.

Considering the degree of accretion on the Lagoon and the impact it will have on the Lagoon and its ecosystem, it is clear that consistent repeated bathymetric data will be suitable to monitor the dynamics of the Lagoon bed. In further investigation, there is need for a multibeam hydrographic data with a high accuracy of depth values.

5.9 Summary of results

This section explores comparative analysis between available two repeated bathymetric data of 2008 and 2014. Overall, Ibeshe region of the Lagoon experienced the largest volume of accretion and it has the widest area covered by accretion. Generally speaking, the total accretion was found higher than the erosion that takes place in the Lagoon. This gives a signal that the depth of the Lagoon is reducing. Joining this finding with one of the inferences in chapter four that shows a reduction in the surface area of the Lagoon due to encroachment on its coastline, it can be concluded that due to increasing urbanisation, the Lagoon is moving toward extinction despite its large area of coverage.

5.10 Concluding remarks

From all the results presented in this chapter, changes exist on the Lagoon bed which is deemed highly significant. Therefore, it is recommended for any future studies there is a need for consistent bathymetric data and that it is acquired with a high level of accuracy. This will help in measuring and monitoring the consistent change on the Lagoon bed and also facilitate decision making for better management of the system.

On the basis of the foregoing evidence from the result in this chapter, it can be concluded that the Lagoon bed sediment is appreciating gradually over years. If proper caution is not taken to monitor the diversion of effluent, erosion and run-off into the Lagoon, in the next few decades the entire Lagoon may have reduced greatly both in plan and depth. With this conclusion, the Lagoon can be managed and sustained from immediate future disappearance by employing consistent maintenance dredging on the Lagoon. Conversely, the cost of doing such consistent maintenance dredging might be too high for the government and hence a pro-active sustainable management of the Lagoon and its ecosystem is the unique solution to the problem.

Although the results of this methodology address a particular lagoon, however, it can be adapted to lagoons and estuaries globally since in the global contest, many lagoons and estuaries are faced with increased urbanisation around their ecosystem and the same forcing conditions are responsible for the changes in the systems. This section has been able to provide a synthesis that can be used globally for sustainable monitoring of the lagoon system in any region of the world.

This chapter has been able to use repeated bathymetric measurements to assess the dynamics of the Lagos Lagoon bed. The assessment revealed that a constant change mostly in terms of accretion takes place on the system's bed. However, there are other sections of the Lagoon bed that experience erosion. The chapter also achieves a major part of research objective three (see Section 1.6 in Chapter 1) which aims at assessing the dynamic nature of the Lagoon and assesses what effect it induces on the Lagoon.

CHAPTER SIX
ASSESSMENTS OF MORPHODYNAMIC INVESTIGATION IN THE LAGOON

6.1 Introduction

This chapter addresses the assessment of the various investigations carried out on the Lagoon's hydrodynamic variabilities both in the dry and wet seasons, the research objectives four and five, and the research question two. It also presents spatial and temporal variation in the Lagoon salinity, temperature and salinity analysis, mixing/spatial stratification, flushing time and spatio particle characterisation on the Lagoon and the result of the model designed to address the influence of sea level effect on the Lagoon ecosystem. The results in this section, even though localised to the Lagos Lagoon in Nigeria, gives an overview of what could be happening to other lagoons in the tropics. Hence, the approach adopted to arrive at the results is partly transferable and can be applied to study the morphodynamic situations in other lagoons especially in the tropical zones. Figure 6.1 shows the various locations on the Lagoon where in-situ hydrodynamic data used in the research were collected during the dry and wet seasons.

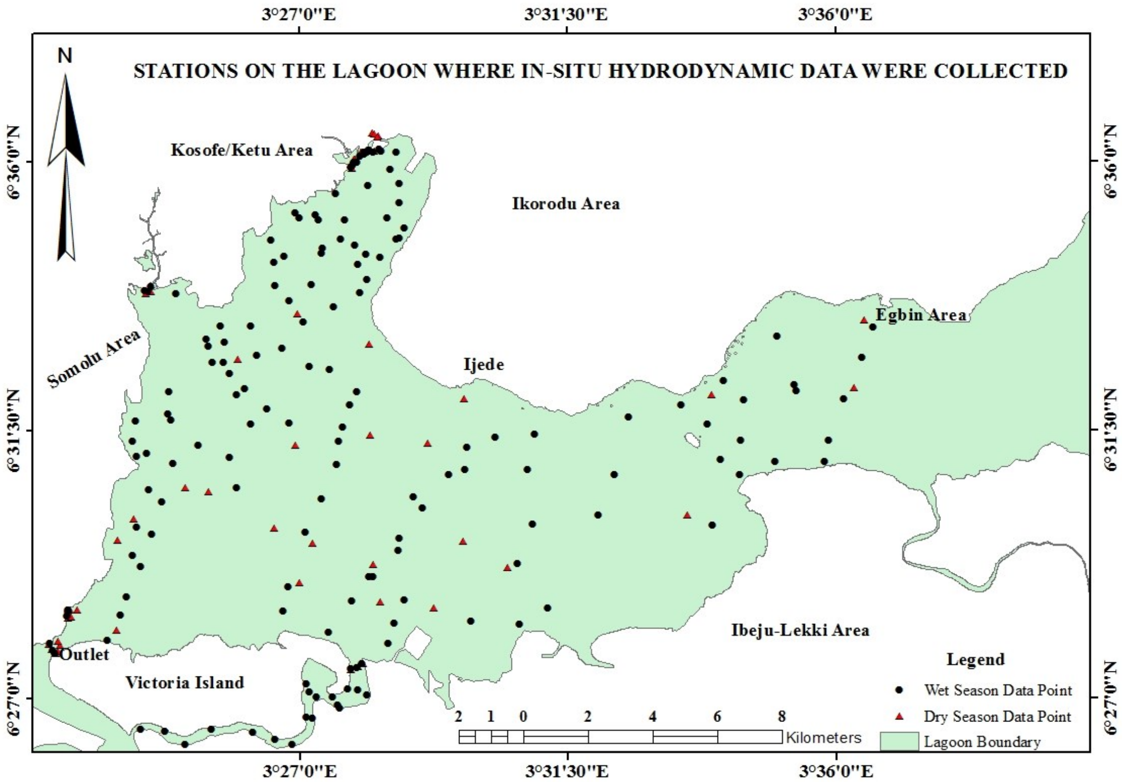


Figure 6.1: Locations on the Lagoon where in-situ hydrodynamic data were collected during the dry and wet seasons. Dry season locations are in triangular red shape while the wet season locations are in circular black shape

6.2 Assessment of salinity pattern at different spatial locations

The current meter data collected on the Lagoon during April and October/November 2014 constitute the dry and wet seasonal data, where salinity data was collected and analysed. Barnes (1980) established that lagoons in the tropic regions are greatly diluted during the wet season by the freshwater from rain and the inflow that comes from river systems, but on the contrary it was noticed that in the dry season when there is extremely high temperature and evaporation that exceeds the freshwater input, salinity rises to a high level.

Six locations (Ogudu Channel area, Carter Bridge area, Ogun and Majidun area, Egbin power station area, Five Cowries and middle of the Lagoon) were chosen for the salinity assessment of the Lagoon. In each of these locations, assessments were based on four states of the tide; these are low water band, high water band, mid-ebb band and mid-flood band.

6.2.1 Salinity assessment during dry season

In order to understand the complex dynamics of the Lagos Lagoon system in terms of temporal and spatial changes of salt intrusion-related conditions, GIS-based techniques were used to prepare these conditions in a map for the different seasons in time and place. This section reveals the dynamics of salt and freshwater intrusion during the dry and wet seasons (with a focus on April 2014 – for the dry season being around 14‰; October, November and partly December 2014 – for the wet season being around 2‰).

The data for the assessment of salinity at the six locations in the Lagos lagoon were not in the same range; the dry season salinity value is of higher range than that of the wet season, this makes it impossible to visually see differences that occur moving from wet season to dry season for a particular tidal band. However, to do a comparative analysis of the dry and wet season scenarios with the associated changes, the data was first normalised before plotting it on ArcGIS environment to make the bin range of the result of the two seasons equal so as to see what change takes place in a particular area of the lagoon moving from one tidal band to another.

To normalise the two season's datasets on ArcGIS, Minus and Divide tools under Math in Arctoolbox were used. After plotting the salinity point data and interpolated using IDW (Inverse Distance Weighting), the generated IDW raster result was used as input raster data on the Minus tool, taking note of the minimum value of the classified IDW raster that is used as input data. The minimum value and the IDW raster dataset serve as a new input data for generating a new raster dataset called, 'norm'.

The same process was repeated but using the Divide tool and rather than using minimum value, the maximum value of the IDW raster and the raster 'norm' were used as new input data. This is done in order to ensure the latest generated raster has its values normalised between the range of 0 and 1.

Table 6.1 shows a summary of the Lagos Lagoon average salinity at four tidal scenarios during the dry and wet seasons. Each of the tidal bands from Table 6.1 also shows percentage rate of salinity decrease at the study region considering the transition from dry season to wet season period. The rate of decrease in salinity values is very high during mid-ebb tide in the entire spatial study region, approximately 99%; this is the highest percentage decrease. Interestingly, the pattern of salinity distribution that prevails in the entire study location on the Lagoon at LW, HW, Mid-Ebb and Mid-Flood band during dry and wet seasons can be clearly visualised in Figures 6.2a to 6.5b.

At Low Water (LW) tide during the dry season, the salinity of the Lagoon (Figure 6.4a) increased from the inlet (Ogun/Majidun area) towards its outlet (Carter Bridge). This is an indication that much of the sea water flows into the Lagoon and drifts northward towards the system inlets and eastward inside the Lagoon. Three of the study locations, Majidun/Ogun River (inlet region), Ogudu channel area and Egbin PS area have a prevailing low salinity of between 8‰ -12‰. In contrast, the outlet area has a salinity range between 24‰ - 29‰, while at the middle of the Lagoon the prevailing salinity average is 13‰.

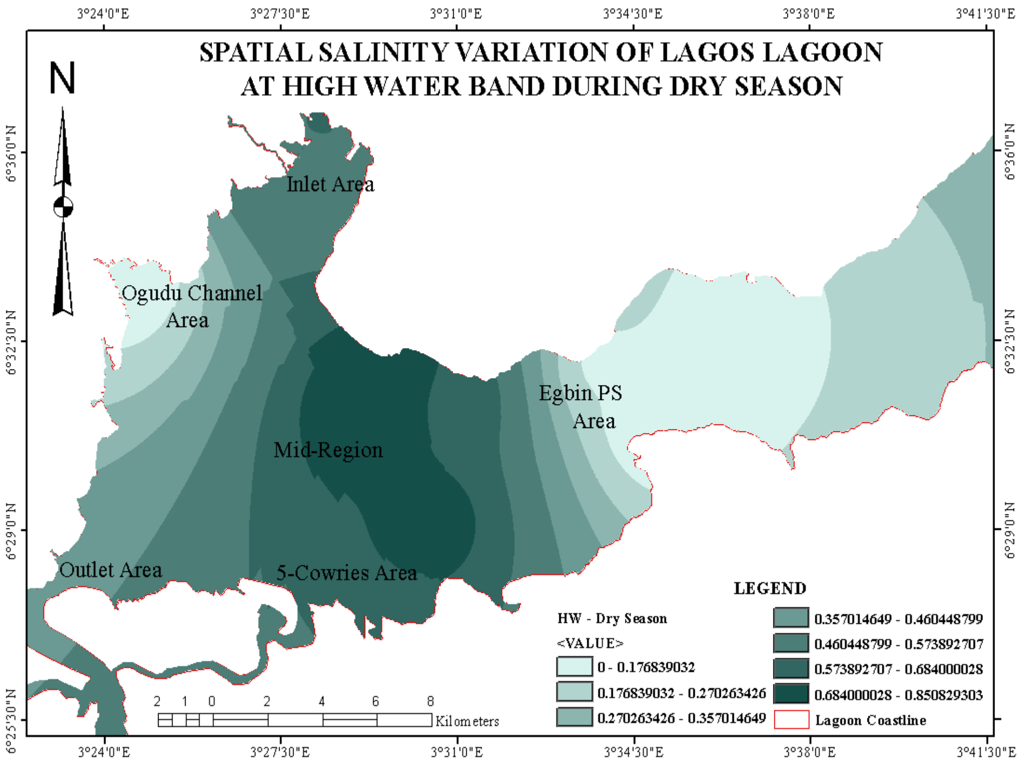
In contrast, during the high water (HW) band, the mid-region of the study location has a high salt wedge that decreases eastward and westward of the Lagoon. However, the Ogudu channel area and Egbin PS has the lowest salinity situation.

A further investigation on the salinity situation during the dry season at the Lagoon was carried out by assessing what happened during the mid-ebb and mid-flood bands (Figures 6.3a and 6.5a respectively). The Lagoon state of tide was defined in this section with respect to Lagos datum as time of observation relative to high water. At mid-flood band, the Lagoon water pushes salt water northward and eastward while at mid-ebb salt water flushes back to the outlet region; this increases the salinity of Carter Bridge area to an average of 26‰.

Two factors might have contributed to the scenario happening at Ogudu channel area during HW and LW bands, it could be as a result of mud deposition and an artificial defence built by local fishermen, the artificial defence is built purposely for hunting fishes in the Lagoon. This local defence mechanism made of shrubs has grown up and formed a barrier line between the Ogudu Channel area and the main Lagoon. As a result of the barrier, sediments from upland through the channel are hindered from flowing freely into the Lagoon; hence deposition is concentrated around the Ogudu channel region approximately 3km into the Lagoon from the channel mouth. The field data collection carried out in April and October/November 2014 serves as an in-situ check that confirms this. This result infers that accumulated mud that eventually changing the area to an inaccessible segment of the Lagoon. It could be inferred from this result that during the dry season the lagoon could be confirmed as brackish water zone because of the salinity range of the system, averagely 20‰.

Table 6. 1: The Table shows a summary of the Lagoon average salinity variation at six spatial locations under the four tidal scenarios. (a) The outlet has the largest range of salinity value at Low Water tide and Mid-Ebb tide, an indication that during wet season high inflow of freshwater is experienced in the area. This resulted in very low salinity value. But, the dry season encounters high salinity value which is an indication that there is very low freshwater inflow through the outlet at this season. (b) Contrariwise, the inlet range of salinity was very small at low water tide compare to that of the outlet. However, the range of salinity variation was high during Mid-Flood tide. At Mid-Flood tide all the six locations experience a high range of salinity variation

Location	Ave. Salinity at LW			Ave. Salinity at HW			Ave. Salinity at Mid-Ebb			Ave. Salinity at Mid-Flood		
	Dry Season(‰)	Wet Season(‰)	% Decrease	Dry Season(‰)	Wet Season(‰)	% Decrease	Dry Season(‰)	Wet Season(‰)	% Decrease	Dry Season(‰)	Wet Season(‰)	% Decrease
Inlet Area	10	0.6	94	9	0.2	97.8	12	0.14	98.8	19.7	0.65	96.7
Ogudu Area	10	2.2	78	4	2	50	16	0.13	99.2	19.7	0.35	98.2
Outlet Area	26	0.6	97.7	7.5	0.2	97.3	27	0.13	99.5	20	1.1	94.5
Mid-Region	13.5	0.1	99.3	12	0.2	98.3	15	0.13	99.1	19.7	1.4	92.9
Five-Cowries Area	13.5	0.6	95.6	9	0.2	97.8	19	0.13	99.3	19.9	1.4	93
Egbin PS Area	10	0.1	99	4	0.2	95	16	0.12	99.3	19.7	1.1	94.4



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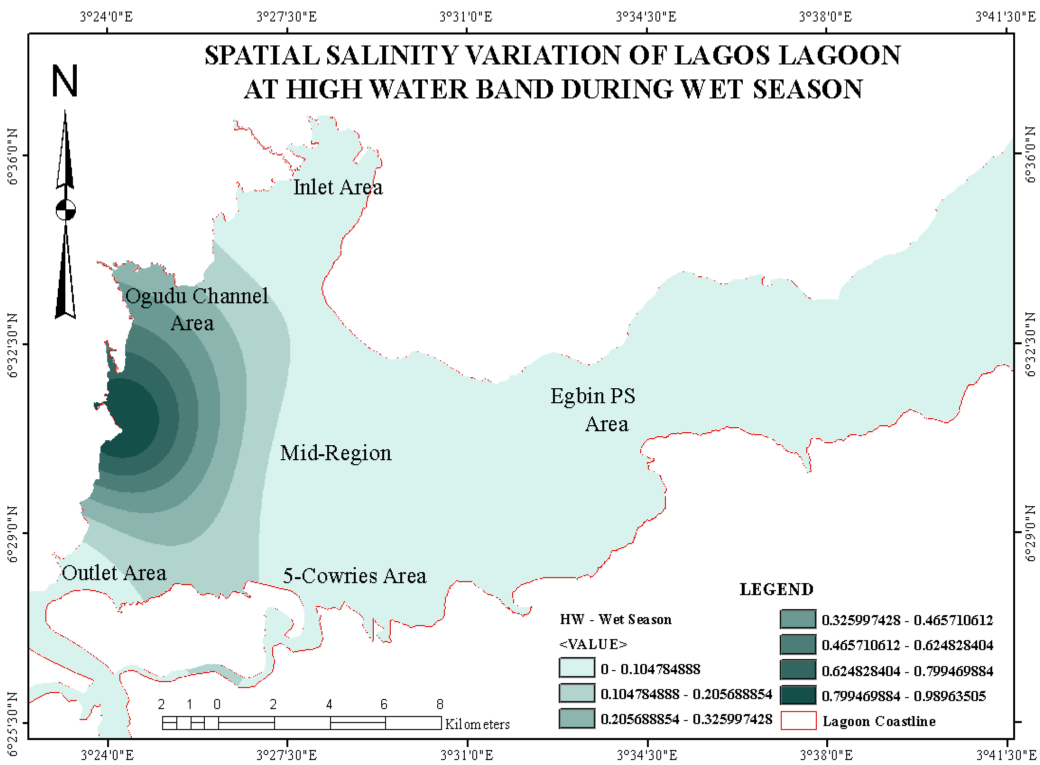
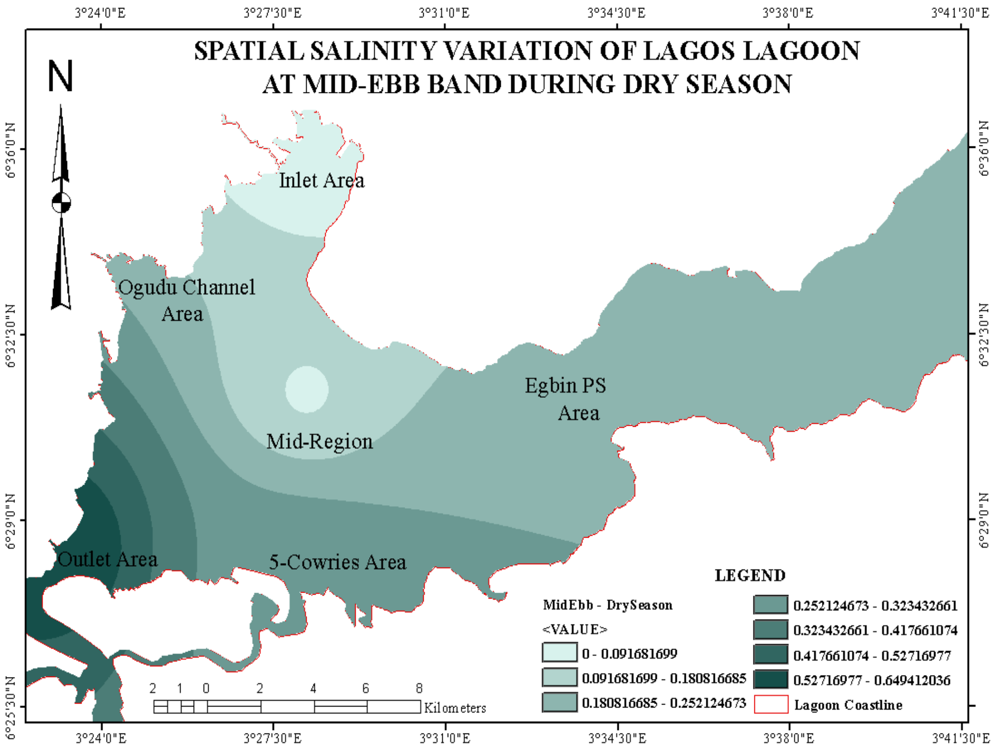


(b)

Figure 6.2: Map of Lagos Lagoon showing spatial salinity distribution at HW during dry and wet seasons. Salinity range (a) dry season is approximately 2‰ - 17‰ (b) wet season is approximately 0.06‰ - 6‰



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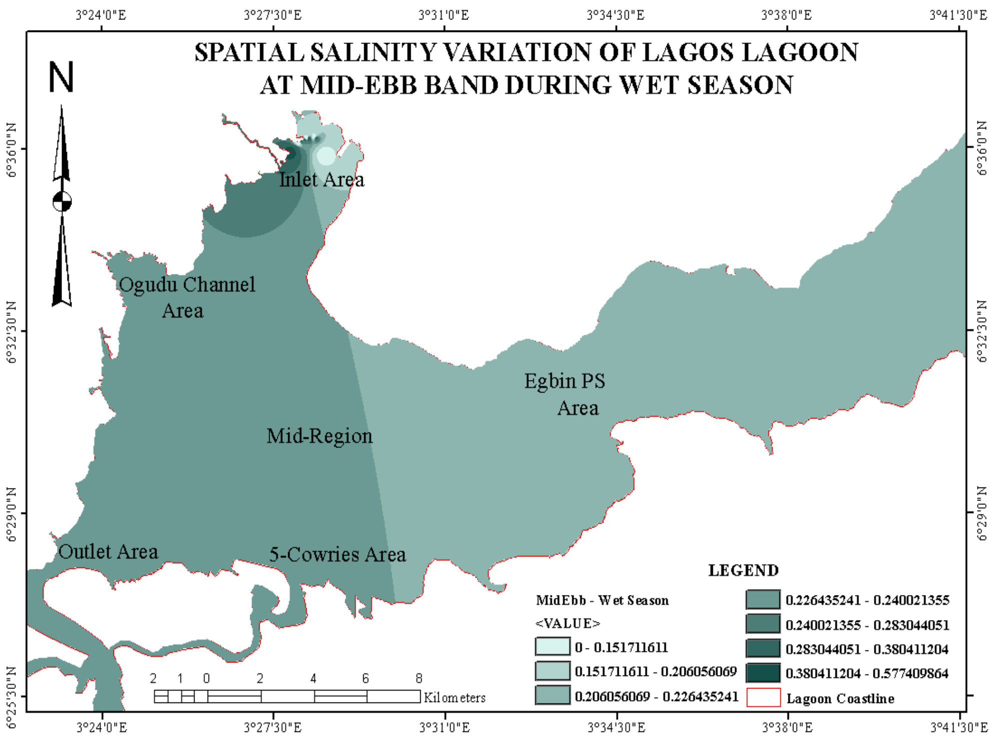
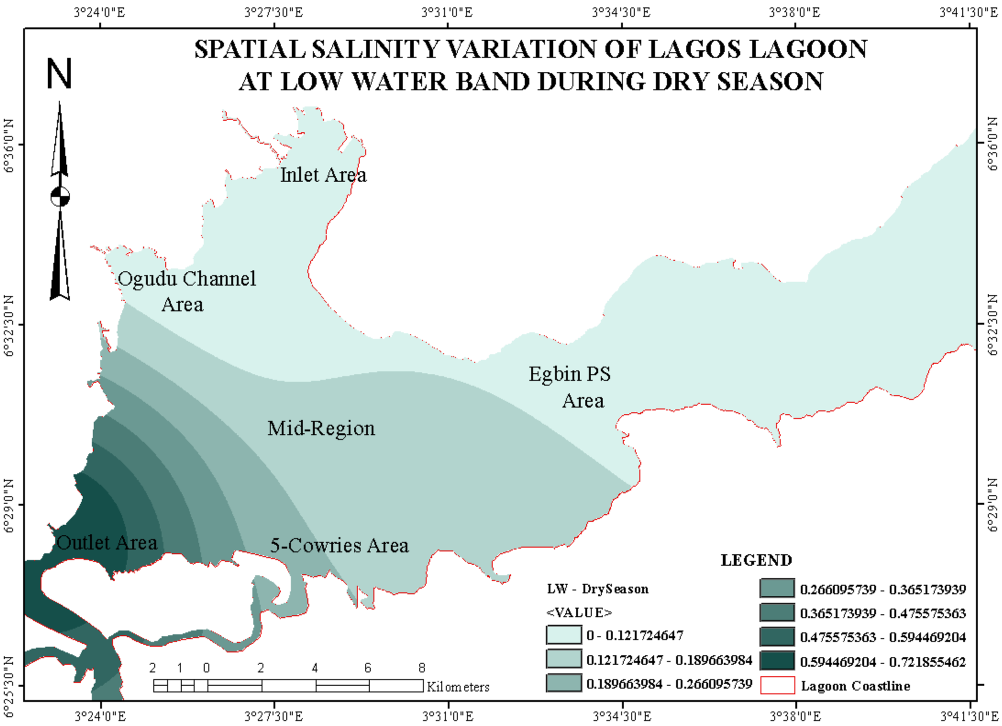


(b)

Figure 6.3: Map of Lagos Lagoon showing spatial salinity distribution at Mid- Ebb during dry and wet seasons. Salinity range (a) dry season is approximately 10‰ - 29‰ (b) wet season is approximately 0.08‰ – 0.2‰



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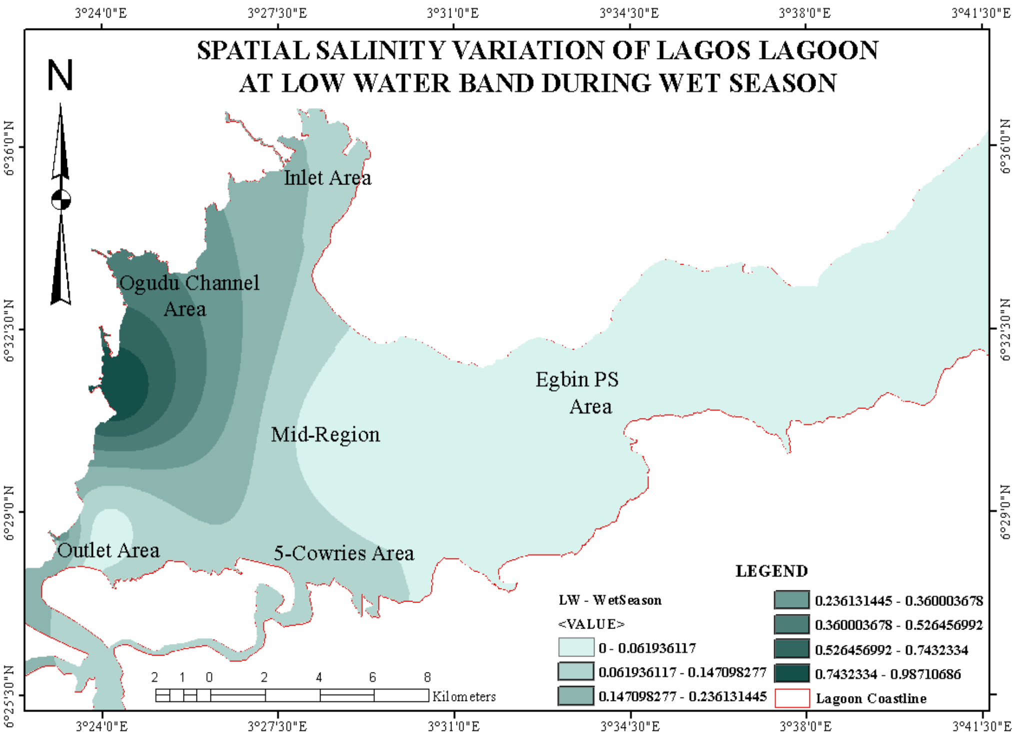
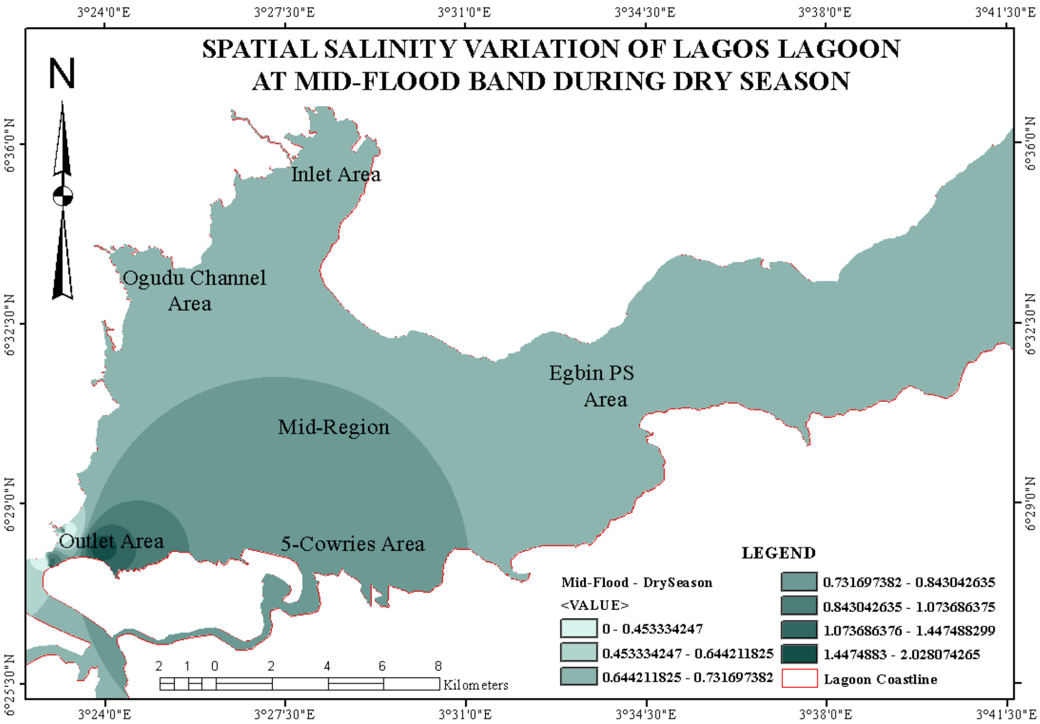


(b)

Figure 6.4: Map of Lagos Lagoon showing spatial salinity distribution at LW during dry and wet seasons. Salinity range (a) dry season is approximately 8‰ - 29‰ (b) wet season is approximately 0.06‰ - 5‰



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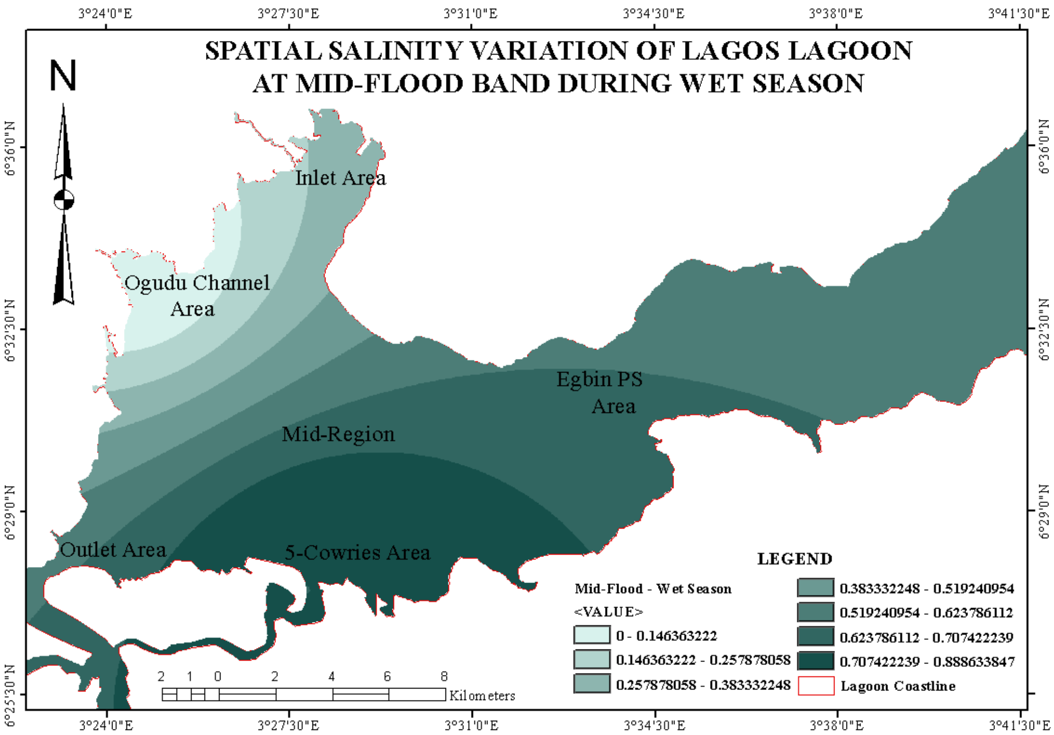


(b)

Figure 6.5: Map of Lagos Lagoon showing spatial salinity distribution at MidFlood during dry and wet seasons. Salinity range (a) dry season is approximately 14‰ - 21‰ (b) wet season is approximately 0.21‰ - 2‰

6.2.2 Salinity assessment during wet season

The Lagoon experiences much inflow of freshwater input and fresh rainfall during the wet season. Figure 6.6 shows the rainfall trend during 1975 and 2012. The high volume of rainfall was encountered in wet season, 176.23mm compared with 107.95mm during the dry season. The impact of a high volume of rainfall with the freshwater inflow through the river channels is a major factor that reduces the salinity gradient experienced in the Lagoon during the wet season. This section examines the nature of changes experienced by the salinity of the Lagoon during LW, HW, Mid-ebb band and Mid-flood band considering the data of wet season (Figures 6.2b, 6.3b, 6.4b and 6.5b).

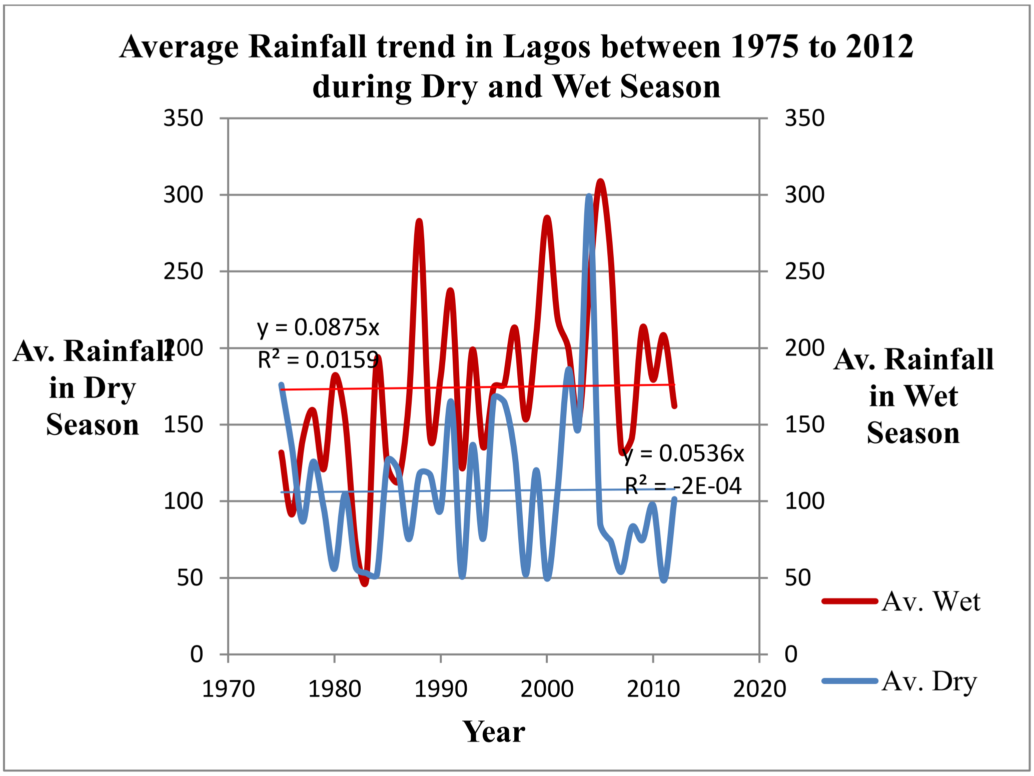


Figure 6.6: Average rainfall in Lagos Nigeria between 1975 and 2012 during dry and wet season (Data source: Nigeria Meteorological Agency – NIMET, Lagos)

Contrary to the result of salinity variations at LW during the dry season, the spatial distribution of the Lagoon salinity at LW during wet season decreases from the eastern region westward. This can be seen in Figure 6.4b, from the mid-region of the Lagoon to Egbin and rest eastern region has approximate salinity range of 0 – 0.062‰, even though under the same conditions, the range of salinity at Ogudu channel area (0.36 – 0.99‰) was a bit higher than what prevails at the mid-region toward Egbin. From the mid-region of the Lagoon during LW, the spatial distribution of salinity during the wet season revealed that salinity decreases to a minimum average of 0.75‰, whereas during the dry season, the average salinity of the area at LW is approximately 14‰ this is about 95% decrease, a proof that large volume of freshwater and rainfall impact on the salinity variation of the system, hence a significant decrease in salinity.

During the dry season at LW, the highest salinity value of approximately 28‰, was recorded around Carter Bridge (the Lagoon outlet), the salinity decreases to a minimum of approximately 11‰ at the extreme northern part of the Lagoon where the two river inlets are situated. Contrasting the mid-ebb band with the mid-flood band during the wet season, the salinity gradient increases from Five Cowries outlet northward during the mid-flood until the minimum range of salinity (0-0.146‰) was attained around the Ogudu region, see Figure 6.5b. However, under the mid-ebb situation only extreme small northern portion of the Lagoon experienced an extreme low salinity gradient. Figure 6.3b shows three major prevailing salinity situations on the Lagoon at mid-ebb, (i) from the mid-region of the Lagoon towards Egbin PS, same salinity range of 0.21‰ – 0.23‰ (ii) From the west to mid-region and covering up to some points in the north region, the salinity range was from 0.24‰ – 0.28‰, (iii) The extreme northern part has a mixed situation; the salinity gradient was higher at the inlet mouth and decreased gradually towards the north east. The highest average salinity during the mid-ebb at wet season is experienced at the southern portion of the Lagoon as 1.6‰.

In conclusion, the high inflow of freshwater and abundant rainfall during the wet season impacts a wide margin of change on the Lagoon salinity gradient. Simply put, the wide salinity variation between dry and wet seasons, confirmed that the Lagoon is a fresh water entity during the wet season and brackish water at the dry season.

6.3 Relationship between observations related to HW and time of observation

As defined by Schmuller (2013), correlation could be termed as a statistical way of looking for rise or fall in relationship that exists between two variables. Hence, measurement of strength and direction of the relationship between the two variables is made possible.

The Pearson correlation between the observations related to HW and time of observation for both the dry and the wet season data were analysed; it shows a negative Pearson correlation value of -0.527 for dry season and 0.070 for wet season. The numerical strength of the Pearson value for the dry season observations indicates a negative average correlated relationship (see Figure 6.7), while for the wet season the numerical strength of Pearson value shows a very weak positive correlated relationship (Figure 6.8). During the dry season as time of observation increases from early hours of the day to late hour of the day, many of the observations moved towards the time of Low Water (LW). Antithetically, as the time of observation increases during the wet season from early to late hours of the day, average observations move towards the time of High Water (HW). From the two observation periods, it can be deduced that the Lagoon experienced much of LW scenario in the dry season from the early hours moving towards late hours of the day. Conversely, during the wet season, the HW scenario prevails on the Lagoon moving from the early hours of the day to the late hours. The tidal forcing mechanism of the Lagoon is the driving force that brings about the difference in the relationship observed in Figures 6.7 and 6.8

A further illustration of the relationship between the observations related to HW and the time of observation in the Lagoon, as shown in Figures 6.7 and 6.8, does not indicate that the plotted data points that are far from the original regression line are outliers. The major reason that accounted for the nature of the graph was that the observation was not continuous all the hours of the day the observations were carried out. Hence, continuous information that displays how the two variables co-vary together was available.

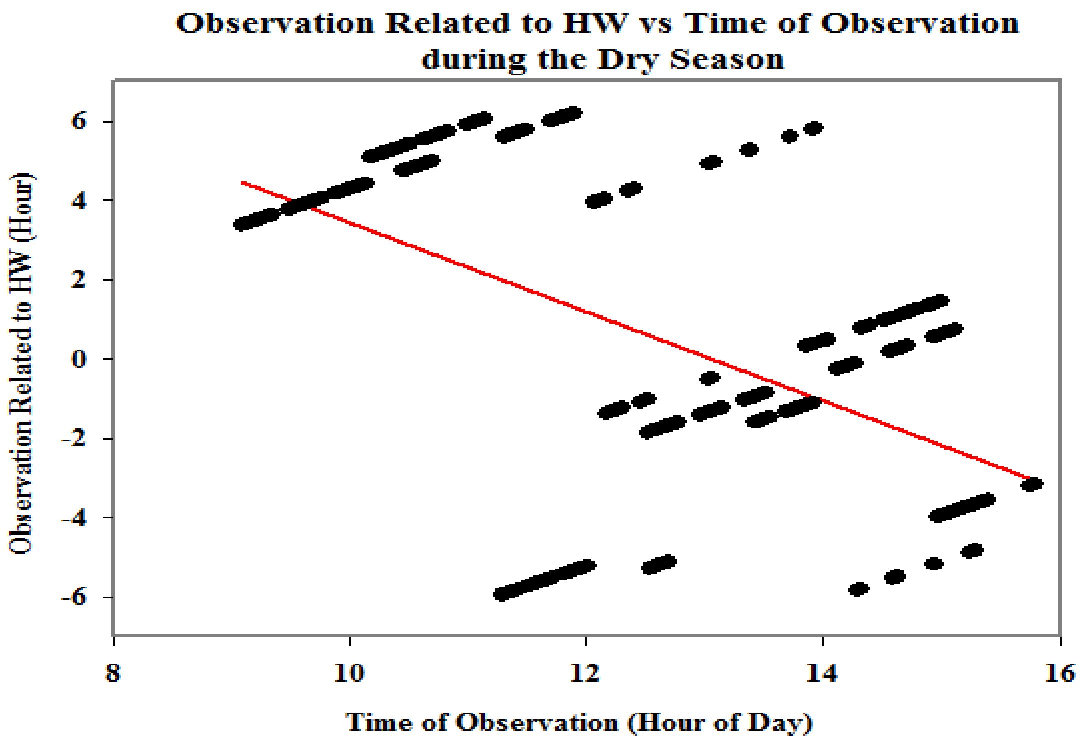


Figure 6.7: Scatter plot showing correlation between observations related to HW versus time of observation during dry season

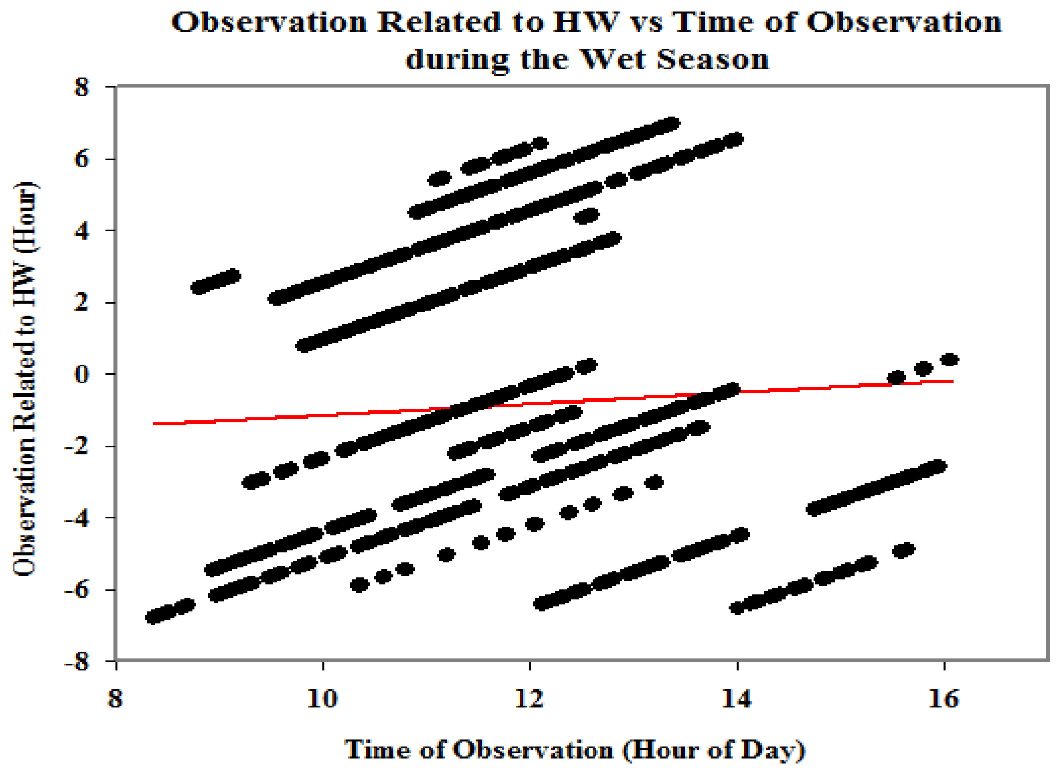


Figure 6.8: Scatter plot showing correlation between observations related to HW versus time of observation during wet season

Further test (ANOVA) was performed over the observation related to HW and time in hour during dry and wet seasons at 95% confidence level. The test revealed statistically significant relationship between the two variables, observation related to HW and time for the two seasons (dry and wet) because the two p-values obtained are less than 0.05; Table 6.2 gives the comprehensive summary of the ANOVA test.

Table 6.2: ANOVA test that shows the result of variability relationship between observations related to HW and time of observation on the Lagoon during dry and wet season

Response variables	p-value	Correlation coefficient	r-squared
Observation related to HW (dry season)	**0.000**	-0.527	0.27731
Observation related to HW (wet season)	**0.000**	0.070	0.004852

The r-squared statistics from the ANOVA test indicates that, for the wet season only 0.48% of the variability in observations related to the HW depends on time of observation; hence the salinity variation during the wet season over a large spatial range on the Lagoon might not be noticed; the salinity of the Lagoon to a large extent is uniform. But during the dry season, 27.73% of the Lagoon variability in observations related to the HW depends on time, and hence salinity varies spatially with time and tidal band on the Lagoon.

6.4 Spatio-temporal analysis of the Lagoon salinity

This analysis was carried out to help assess the spatial and temporal variability in the salinity impact on the Lagoon. From the general archive of the data from Valeport Current meter, the salinity of six locations around the Lagoon was extracted as sub-data from both the wet and dry season data. The extracted salinity results from the two observation campaigns were linearly regressed against time to generate further results; the results are the regression slope, regression coefficient, and p-value (Table 6.2). Figure 6.9 shows salinity against month of the year for the spatio-temporal analysis on the Lagoon. April was a dry season period where salinity value was very high but the remaining three months (October, November and December 2014) are within the wet season period, with the lowest salinity recorded in October. The mean and standard deviation of the salinity values were computed for each month.

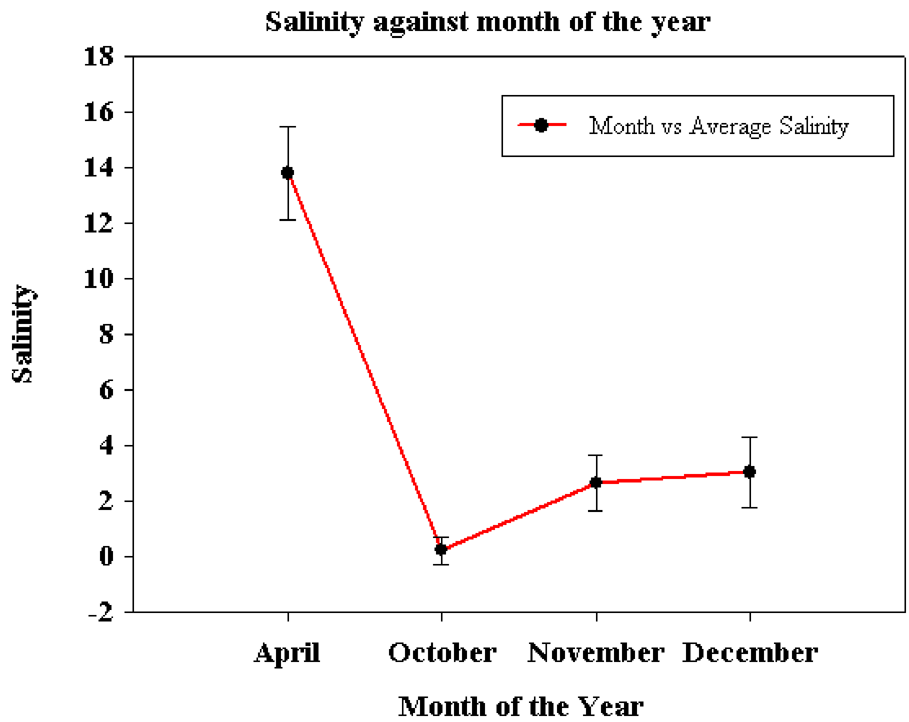


Figure 6.9: Salinity against month of the year for spatio-temporal analysis of the Lagoon at different months. This shows the distribution of the Lagoon salinity based on wet and dry seasons

Table 6.3: Linear regression result of the extracted salinity data regressed against time of observation

Month of the Year	**Regression slope**	**Regression coefficient**	**r^2**	**p-value**
April	-0.0235	-0.244	0.059	0.069
November	-0.0063	-0.109	0.012	0.407
December	-0.0137	-0.186	0.035	0.155

Table 6.3 shows the salinity variation on the lagoon in respect to the month of data collection. The p-values show where the relationship is statistically significant at significant level of $\alpha > 0.05$. The result shows that none of the salinity data in any of the months adopted has significant correlation with the time at which the data was gathered.

The month of April has some small level of correlation because of the p-value result (0.069). During this period, there is not much rainfall and the rate of freshwater inflow from the rivers that feed into the Lagoon is very low. Hence, the spatial change in the salinity is partly dependent on time of the day when tidal scenario changes.

A further analysis on the salinity and temperature values on the two seasons were carried out based on data collected at six locations on the Lagoon. The locations were chosen based on where saline and fresh water flow into the Lagoon and also a neutral location inside the Lagoon. Salinity and temperature values for these six locations were extracted with the time of data collection. The extracted variable data of each of the locations were regressed against the time of observation.

The linear regression analysis for the six spatial locations were summarised in Figures 6.10 – 6.16 and Tables 6.4, 6.5, 6.6 and 6.7. The scales of correlation coefficient of the temperature do show partly strong seasonality – that is generally regular and periodic (0.838, 0.703, – 0.827); fairly strong seasonality (0.680, 0.641 and 0.544) and partly a weak seasonality ranging from -0.059 to 0.469. The lowest correlation (-0.059) existed at the Inlet during the dry season indicating that there is no significant relationship between the temperature variation and the time of observation. On the other hand, the salinity correlation was slightly different from that of the temperature, it depicts in five of the locations strong correlation (both positive and negative) and average correlation in three locations.

At the inlet and Ogudu Channel during the dry and wet seasons, the correlation coefficients for the variability of temperature and salinity were both positive (Tables 6.4 and 6.6), the consequence was that the two variables increase with time regardless of the season of observation. However, low salinity against high temperature was the result deduced from Ogudu Channel (Figure 6.10a and 6.10b) during the dry and wet seasons but as the time of observation increases during the wet season, the temperature goes down while salinity increases. Generally, there was consistent seasonality in the variability of the salinity and temperature at the outlet region. As salinity increases temperature decreases both at the dry and wet season (Figure 6.11a and 6.11b).

At the Five-Cowries and Egbin, the salinity and temperature variabilities show that low salinity variability was experienced at Five-Cowries (26.7%) and Egbin (22.4%) during the wet and dry season respectively. Conversely, percentage range of temperature variability at the locations was at close range, 42.1% and 49% during the dry and wet seasons respectively.

The inlet experiences the lowest salinity (6.4%) and temperature (0.3%) variabilities during the dry season, in contrast with percentage variability of 68.1% during the wet season. The consequence is that high volume of fresh water enters through the inlet during the wet season. At the Mid-Region, the difference in the percentage variability of the Lagoon salinity was somehow close; this is an indication that during the dry and wet seasons, in daily tidal cycle, the variation in the Lagoon surface salinity is not much. Hence, it is possible to predict the range of salinity variation at the mid-region any time of the day, however, temperature increases with time at both wet and dry season.

The full range of salinity trend for the six locations during the dry season is between approximately 2‰ – 19.1‰ with p-value from $3.7 \times 10^{-26}$to 0.0001 but during wet season the range is between 0.055‰ and 1.92‰ with p-value from 8.92×10^{-40} to 0.049 (from Figures 6.10 – 6.16 and Table 6.4).

Table 6.4 shows that five out of the twelve relationships were positively correlated meaning that salinity increased with increase time of observation. The strongest positive correlation relationship occurred during the wet season at the inlet (0.825) followed by Ogudu Channel (0.737), while the least correlation is at the outlet during the wet season.

Table 6.4: Computed values of r^2, correlation coefficient and p-value with 95% confidence level using extracted salinity and the time of observation at six spatial locations on the Lagoon

Location	Season	r^2	Correlation coefficient	p-value
Ogudu Channel	Dry	0.182	-0.426	1.9×10^{-10}
	Wet	0.544	**0.737**	5.5×10^{-12}
Outlet	Dry	0.372	-0.700	3.7×10^{-26}
	Wet	0.572	0.239	**0.049**
Five-Cowries	Dry	0.421	-0.649	1.1×10^{-11}
	Wet	0.267	-0.517	1.7×10^{-8}
Egbin	Dry	0.224	-0.474	0.0001
	Wet	0.490	-0.701	2.0×10^{-14}
Inlet	Dry	**0.064**	0.253	0.0007
	Wet	**0.681**	**0.825**	8.92×10^{-40}
Mid-Region	Dry	0.492	-0.701	3.3×10^{-7}
	Wet	0.330	**0.575**	5.7×10^{-8}

The remaining seven relationships showed negative correlation, indication that as time of observation increases salinity decreases along. The strongest negative correlation occurred at Egbin and the Mid-Region (-0.701) during wet and dry season respectively followed by the outlet (-0.700), while the least negative correlation was at Ogudu Channel (-0.426) during dry season. Conversely, four of the temperature variability (Table 6.5) was positively correlated while the remaining eight were negatively correlated. The strongest positive correlation was at the inlet during wet season while the strongest negative correlation was at Ogudu Channel.

Table 6.5: Computed values of r^2, correlation coefficient and p-value with95% confidence level using extracted Temperature and the time of observation at six spatial locations on the Lagoon

Location	Season	r^2	Correlation coefficient	p-value
Ogudu Channel	Dry	0.195	- 0.441	3.7×10^{-11}
	Wet	0.463	- 0.680	8.7×10^{-10}
Outlet	Dry	0.072	- 0.268	2.28×10^{-5}
	Wet	0.219	- 0.469	0.0001
Five-Cowries	Dry	0.122	- 0.349	0.0009
	Wet	0.411	**0.641**	1.69×10^{-13}
Egbin	Dry	**0.046**	- 0.215	**0.091**
	Wet	**0.683**	- 0.827	1.91×10^{-23}
Inlet	Dry	**0.003**	- 0.059	**0.438**
	Wet	**0.702**	**0.838**	4.378×10^{-42}
Mid-Region	Dry	0.494	**0.703**	2.96×10^{-7}
	Wet	0.296	**0.544**	3.88 x 10-7

Further analysis was carried out on the combined salinity-temperature data; this was regressed linearly against their time of observation respectively. The percentage variability of the Lagoon salinity and temperature were very low during the dry and wet seasons (Table 6.6 and 6.7). The Lagoon's salinity and temperature variabilities during the dry and wet seasons were 5.9% and 3.2%; 8.6% and 9.2% respectively. This indicates that the range of salinity was lower during the wet season than that of dry season. Whereas the range of temperature value was lower during the dry season compare to that of the wet season. The p-value values for dry and wet season relationships for both salinity and temperature were less than 0.05, meaning that for the two seasons there is statistically significant relationship between observed variables (salinity and temperature) and time of observation. Notwithstanding, the correlation of the relationships were not the same and as well not strong.

Table 6.6: Computed values of r^2, correlation coefficient and p-value with 95% confidence level using extracted salinity and the time of observation during dry and wet seasons

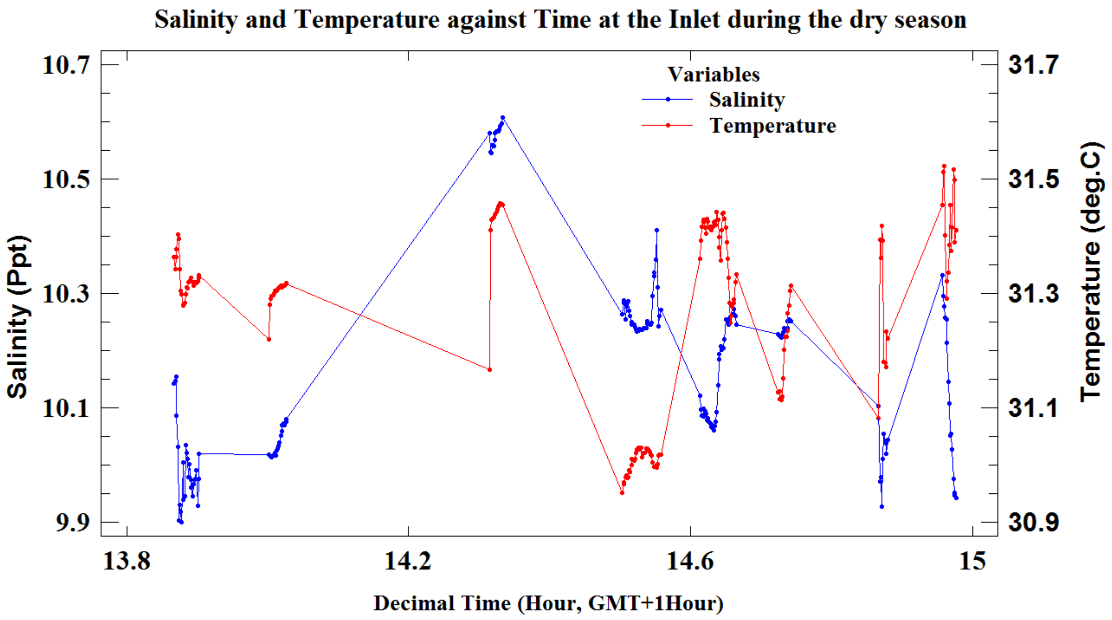
Season	r^2	Correlation coefficient	p-value
Dry	0.059	-0.243	0
Wet	0.032	0.180	0

Table 6.7: Computed values of r^2, correlation coefficient and p-value with 95% confidence level using extracted temperature and the time of observation during dry and wet seasons

Season	r^2	Correlation coefficient	p-value
Dry	0.086	0.293	9×10^{-112}
Wet	0.092	0.303	0

Conclusively, the overall results for salinity and temperature (Figures 6.10 – 6.16) give a reasonable representation of their annual prevailing changes on the Lagoon since there are two seasonal variations in Nigeria. Hence the results attained for the dry and wet seasons are sufficient to give a general situation of the dynamic nature of the Lagoon in terms of variation in salinity and temperature especially around the western region toward the mid region of the Lagoon.

Moreover, the various intercepts in the graphs of salinity and temperature against time of observation (Figures 6.10 – 6.15) also reveal situation where there is possibility of well mixed water mass, that is, a point of distinctive narrow range of temperature and salinity and a particular density resulting from the two parameters (temperature and salinity). The graphs in each Figure 6.10 - 6.15 represent both salinity and temperature data at the surface and inside the Lagoon at six separate locations and the time in decimal hour at which observations were taken. However, Figure 6.16a and 6.16b show the plot of all the salinity-temperature data at all locations during the dry and wet seasons. The data was collected over different days that the data gathering covered during the dry and wet seasons. The dry season data was collected in April 2014 while the wet season data was gathered in October and November 2014. Formation of water mass is a function of the prevailing climate effects in a region, hence the alternate dry and wet seasons in Nigeria affect the Lagoon water mass. Xu *et al.* (2008) confirm the possibility of the water mass occurring at the intersection of salinity and temperature diagram in their study of analysis of water masses in the Northern Pacific Ocean.



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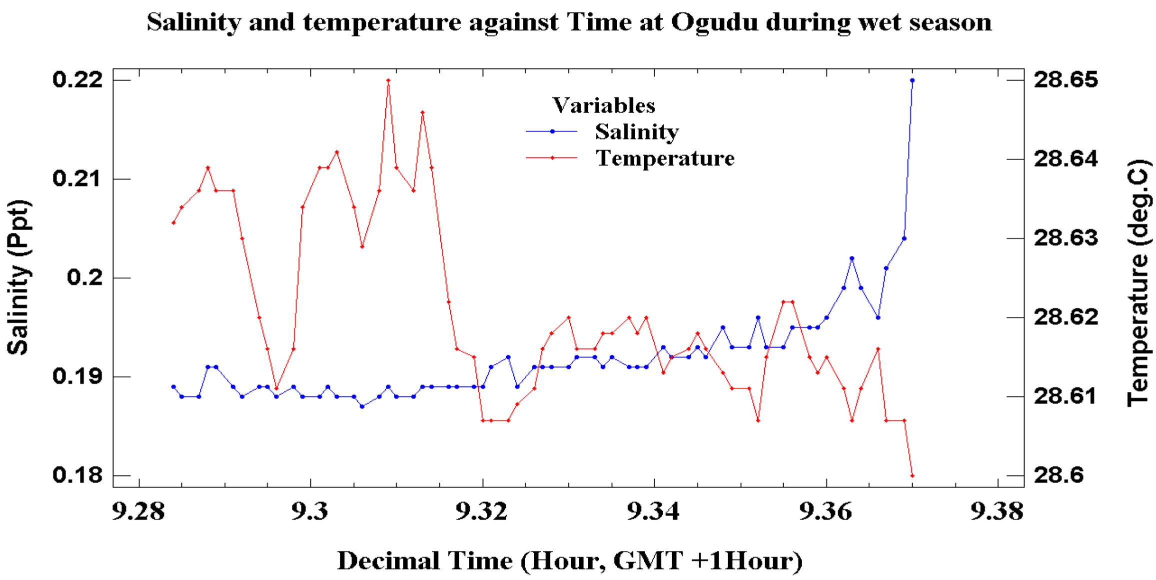

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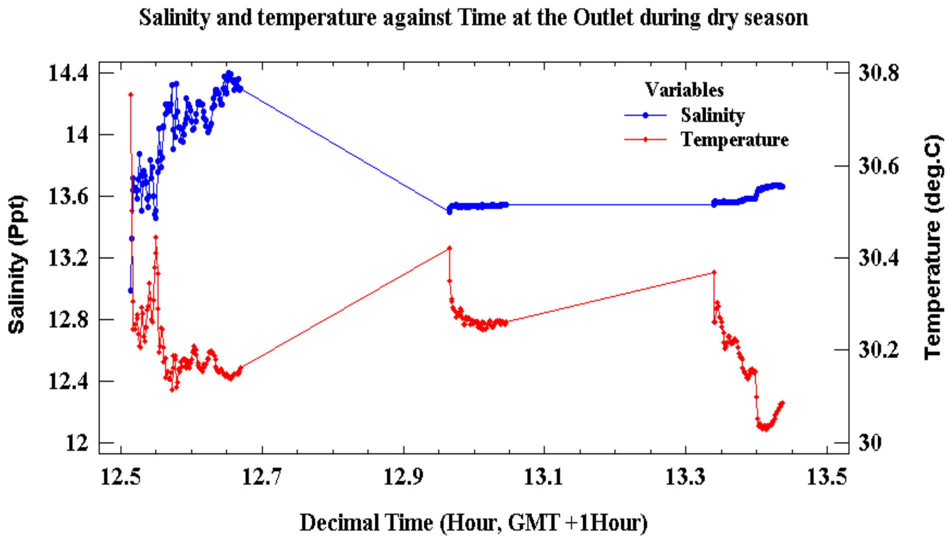
Figure 6.10: Salinity and Temperature variations against Time of observation at Ogudu Channel. (a) Salinity and temperature behaviour during the dry season; (b) Reaction of salinity and temperature during the wet season



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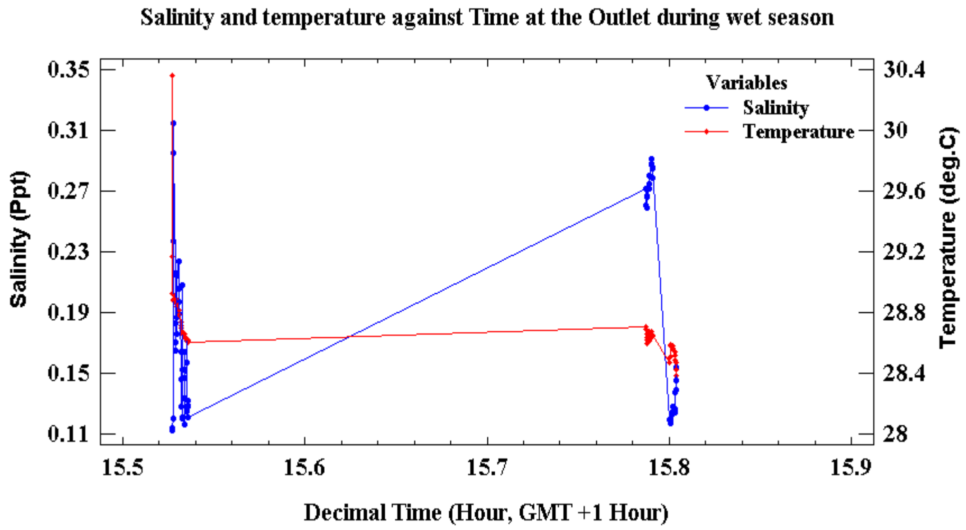

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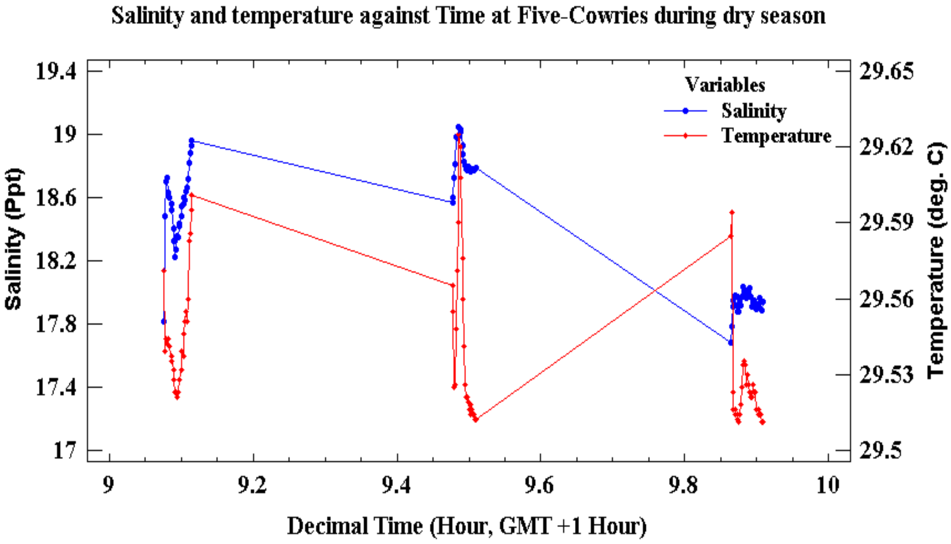
Figure 6.11: Salinity and Temperature variations against Time of observation at the outlet. (a) Salinity and temperature behaviour during the dry season, (b) Reaction of salinity and temperature during the wet season

From the analysis of the salinity-temperature variability with time of observation at the Five-Cowrie region of the Lagoon, there was equal water mass at two different time of the day at both the dry and wet seasons. The consequence is that the density of the water at these times will be equal (see Figure 6.12a and 6.12b).



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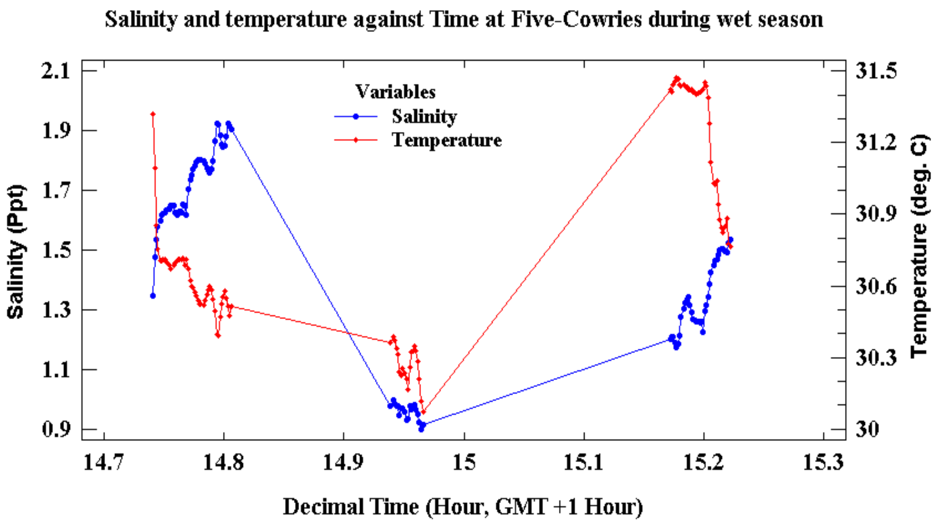

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Figure 6.12: Salinity and Temperature variations against Time of observation at Five Cowries. The Lagoon has equal water mass was found to be the same at about 9:06am and 9:30am; 2:45pm and 3:12pm during the dry and wet season respectively(a) Salinity and temperature behaviour during the dry season, (b) Reaction of salinity and temperature during the wet season

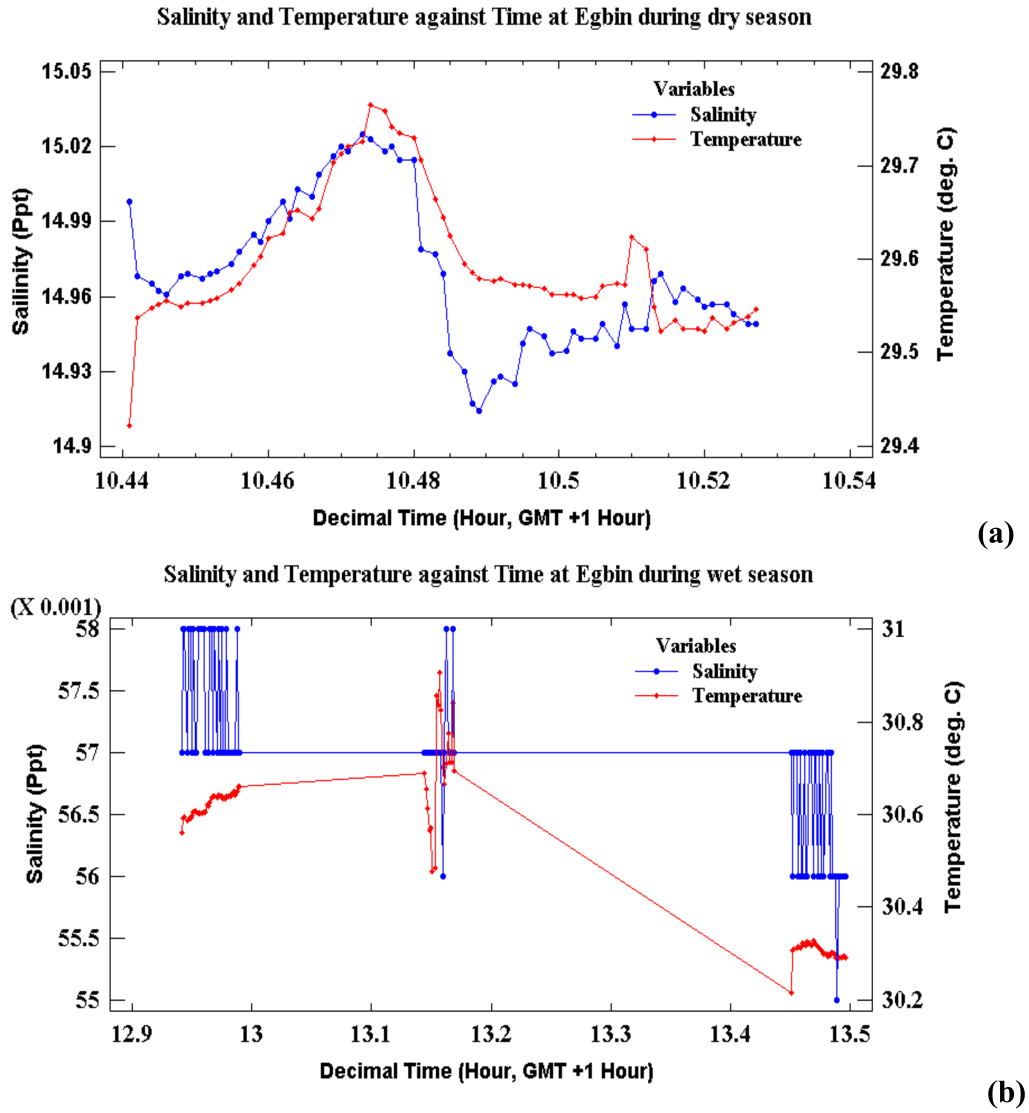
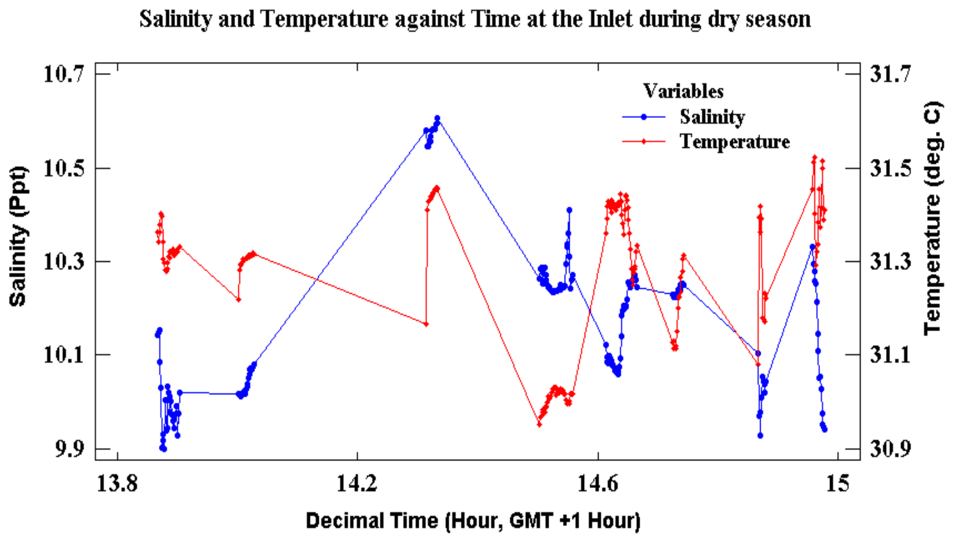


Figure 6.13: Salinity and Temperature variations against Time of observation at Egbin. (a) Salinity and temperature behaviour during the dry season, (b) Reaction of salinity and temperature during the wet season



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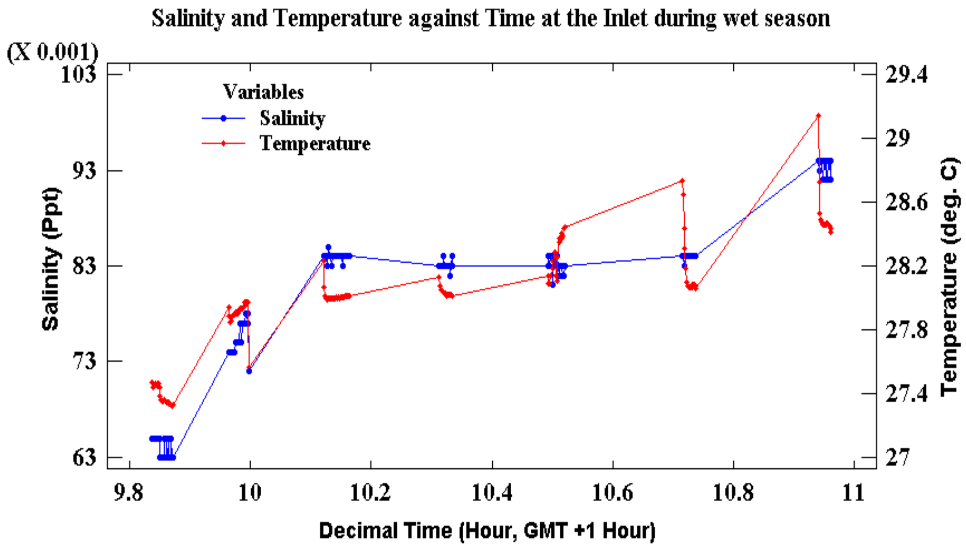

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Figure 6.14: Salinity and Temperature variations against Time of observation at the inlet. (a) Salinity and temperature behaviour during the dry season, (b) Reaction of salinity and temperature during the wet season

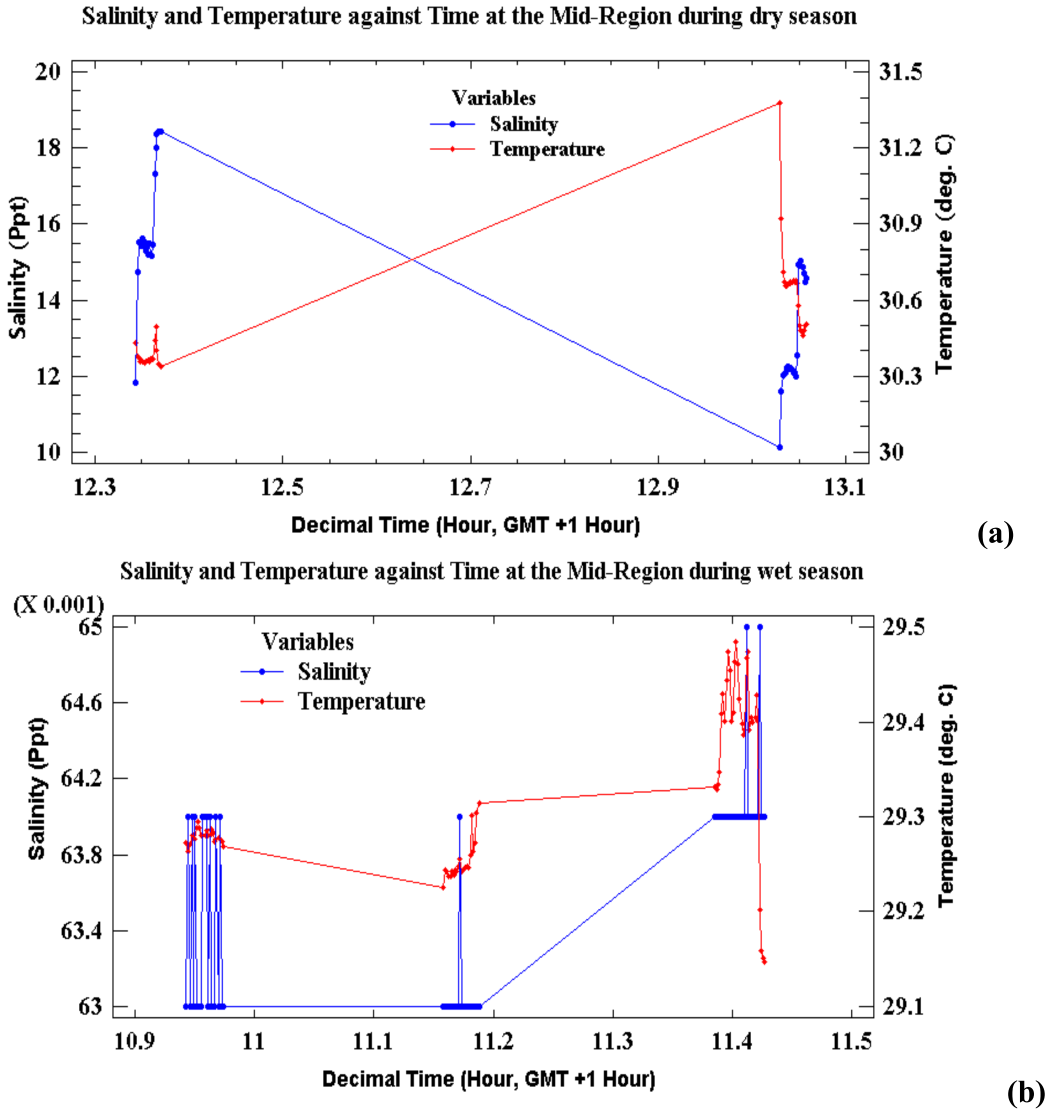
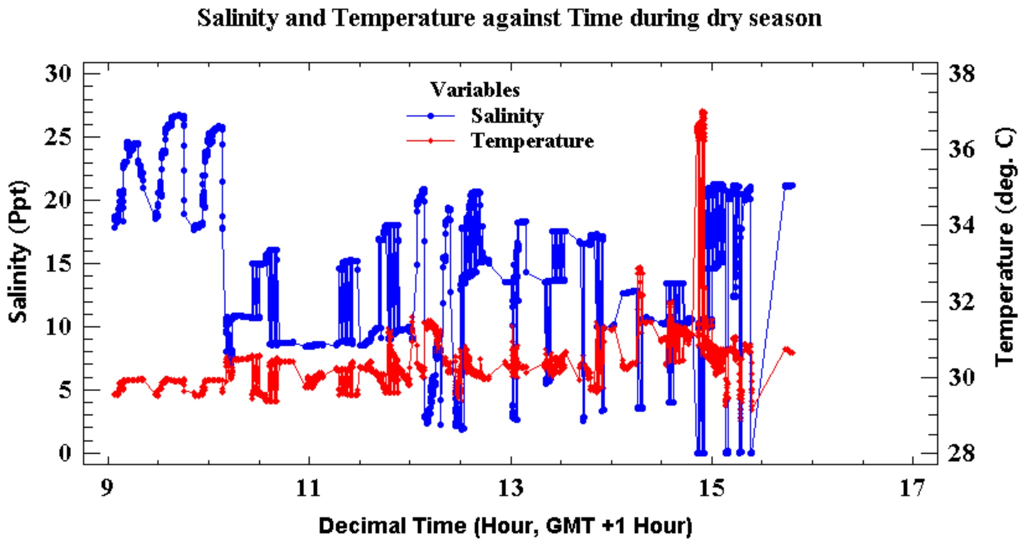


Figure 6.15: Salinity and Temperature variations against Time of observation at the mid-region. (a) Salinity and temperature behaviour during dry season, (b) Reaction of salinity and temperature during wet season

Consequently all data (salinity and temperature) collected during the dry and wet seasons from all data locations on the Lagoon were plotted as shown in Figures 6.16a and 6.16b. It's noteworthy that during dry season (Figure 6.16a) there is constant change of water mass, this is very predominant anytime from 11.45am (approximately). This suggests that at these times of the day there is dominant effect of shear, instabilities and mixing on the Lagoon. Nonetheless, the Lagoon salinity and temperature dynamics during the wet season was completely different (Figure 6.16b); intersection between the graph of salinity and temperature which indicate the possibility of a change of water mass in the Lagoon was not a common situation as it occurred during the dry season (Figure 6.16a), only at two main distinct times (approximately 11.36am and 1.18pm). Aside these two observed times there was no interception at any other points. The implication of the no intersection in the plot of the wet season suggests that small velocity shear is experienced at this time; hence there is stability and no mixing in the Lagoon water. Change of water mass is not prevalence during the wet season; this has also confirmed that the salinity variability of the Lagoon is very stable in wet season. This section has strengthen the results obtained in section 6.1 and confirm that the Lagoon is freshwater entity during the wet season and brackish during the dry season.



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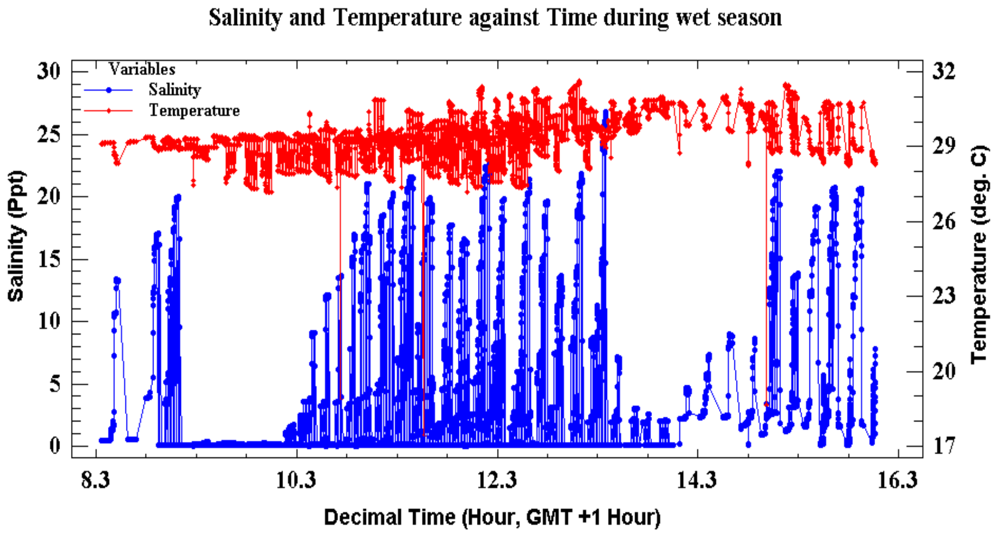


(b)

Figure 6.16: Salinity and Temperature variations against Time of observation on the entire case study area on the Lagoon during dry and wet season. (a) The general behaviour of salinity and temperature during dry season, (b) the reaction of salinity and temperature during wet season

6.4.1 Temperature-Salinity (T-S) diagram analysis

In order to explore more on the prevailing dynamics of the Lagoon, observed salinity and temperature from the Valeport data were extracted and subjected to T-S diagram analysis. This analysis has been applied previously by several lagoons, estuary and oceanography researchers and they recorded reliable inference, for example, Newton & Mudge (2003) use T-S diagram to investigate temperature and salinity regimes in a shallow mesotidal lagoon in order to detect the deterioration of the lagoon water quality. They concluded that an abrupt decrease in salinity but not temperature was probably due to change in water mass or vertical mixing in the water body. Also (Sun *et al.,* 2008) applied the T-S diagram to study the water mass structure in the northwest Pacific Ocean. Their results reveal that is possible to use T-S diagram analysis to structure a water body into component of different water masses in terms of the prevailing salinity variation of such system.

Furthermore, Swerpel & Warszawy (1987) employed T-S diagram method for the assessment of variation of surface water temperature and salinity. In this study, the observed salinity and temperature of the Lagoon were extracted for both dry and wet season and were plotted to obtain T-S diagram. Seasonal variation of the T-S diagrams (Figures 6.17 and 6.18) show that the temperature and salinity variation was more obvious during the wet season where the boundary range of the Lagoon temperature (approximately 27.2°C – 31.6°C) was high at minimum salinity (approximately 0‰) but it converges as the salinity increases. However, the Lagoon T-S variability during dry season behaves differently. Wide range of temperature value was the result in this case, convergence started from salinity value of approximately 21‰. The point where convergence takes place in the two figures suggested critical point (critical state); these points suggest where no phase boundaries exist, an interfacial dynamic zone. This point was noted as salt-free system, it shows a pronounced local maximum and a local minimum temperature found to be ≥25°C in the result of Zhu *et al.* (1992). In this research the values of these points during the dry and wet seasons are approximately 30°C; 27‰ and 28.8°C;26.9‰ respectively.

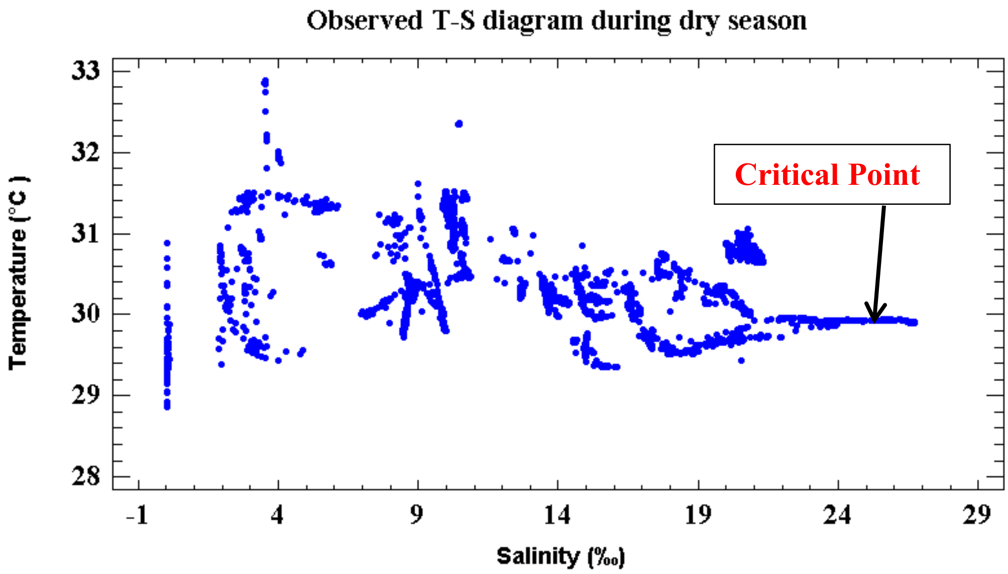


Figure 6.17: Observed T-S diagram of the Lagoon during the dry season

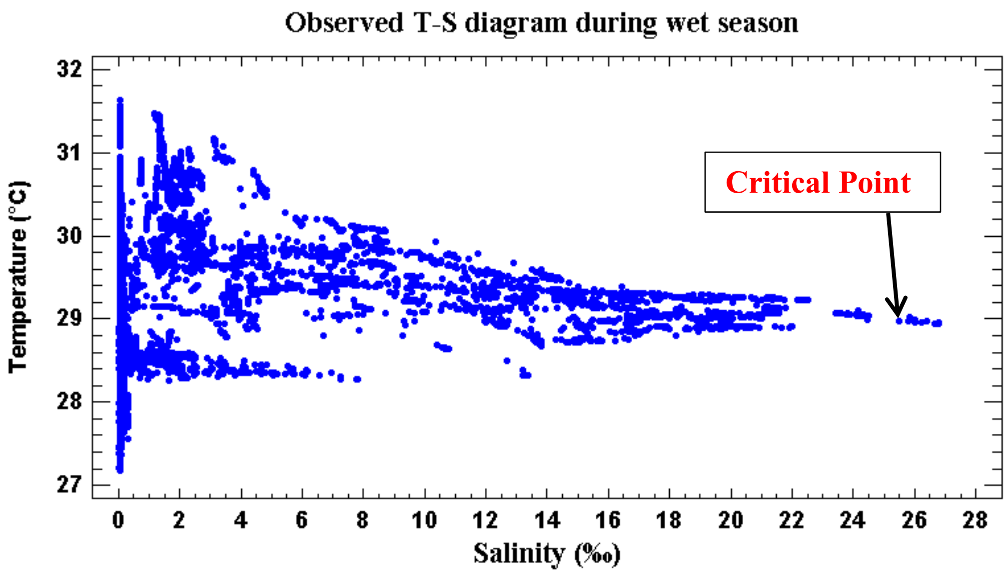


Figure 6.18: Observed T-S diagram of the Lagoon during the wet season

6.5 Spatial variation in salinity intrusion from the outlet

Further to the analysis done in sections 6.3 and 6.4, the salinity values for both dry and wet seasons were extracted from the Valeport current meter considering some points where data was observed along two main transects (outlet to inlet transect and outlet towards Egbin transect). Using the observed coordinates of point of observation, distance from the outlet to each point where salinity was measured along each of the choosing transects was computed against the salinity value at different time related to high water

(HW). The computed distances against salinity were tabulated for both dry and wet season (Table 6.8); graph of salinity against distance was generated in order to see the spatial characteristics of the Lagoon salinity (Figure 6.19) moving from the outlet towards the northern region (inlet) and eastern region (Egbin) of the Lagoon. During the dry season, the salinity along the two transects were almost equal at initial state until a distance of about 17km away from the outlet where the salinity along the inlet transect rises from approximately 8‰ to 11‰ until a distance of 19km away from the outlet. However, along the Egbin transect salinity decreases approximately to 4‰ and remains constant from a distance of about 21.5km to 27km away from the outlet. At the far end of the two transects, salinity values differ by 5‰. Thus it can be inferred that the Lagoon water experiences more freshness farther into the east along Egbin transect than the inlet mouth region. The rise in salinity towards the inlet mouth could be as a result of inflow of small scale industrial and household wastes into the Lagoon in the region.

Along the inlet transect there was a steady decrease in the salinity of the Lagoon during wet season until it reaches minimum value (0‰) at a distance of approximately 14.5km away from the outlet. Conversely, it should be noted that during the dry season the minimum salinity (8.0‰) was not attained until a distance of about 17 km away from the outlet, the saline intrusion goes upstream than in the wet season. This shows the extent to which saline water from the ocean goes into the Lagoon and the minimum salinity value that is attained during wet and dry season. From Figure 6.19, the points where salinity attained the minimum value at the two seasons on each transects could be regarded as point of equilibrium. During dry season, the point of equilibrium was reached along Egbin transect at 21.5km away from the outlet, but along inlet transect, it was reached at a distance of 17.0km away from the outlet. During wet season there was no variation in the salinity along Egbin transect, all values were below 0.1‰. This shows that the Lagoon was fresh water along that direction. However, along the inlet transect, the salinity falls from the maximum (7.8‰) until equilibrium was reached at approximately 14.9km away from the outlet.

Table 6.8: Transects from the Lagoon outlet towards the norther region of the Lagoon (Inlet area) and towards Egbin eastern region of the Lagoon with salinity value at intermittent distance along the transects

Distance from the outlet (km)	Salinity along Egbin transect at dry season	Salinity along inlet transect at dry season	Salinity along Egbin transect at wet season	Salinity along inlet transect at wet season
0	20.391	20.391	0.281	6.74
0.27	19.13	19.13		
1.23		19.111		
2.35			0.084	
3.72		17.67		
3.96				3.795
4.52		17.577		
5.94				3.451
6.60		16.577		3.201
7.70	16.892			
8.00				2.602
8.63			0.065	
9.25				2.349
9.54			0.063	
10.00	15.361	14.06		1.945
11.00				1.584
12.10			0.062	
12.80	13.208	13.539		0.812
13.40			0.061	
14.00	12.206			
14.50				0.162
15.70			0.06	
17.30		8.004		
18.00		8.539	0.056	
18.50		10.054		
20.00	5.96			
21.50	4.002		0.056	
24.30			0.057	
26.00	3.363		0.057	
27.00	3.521		0.057	
27.20			0.057	

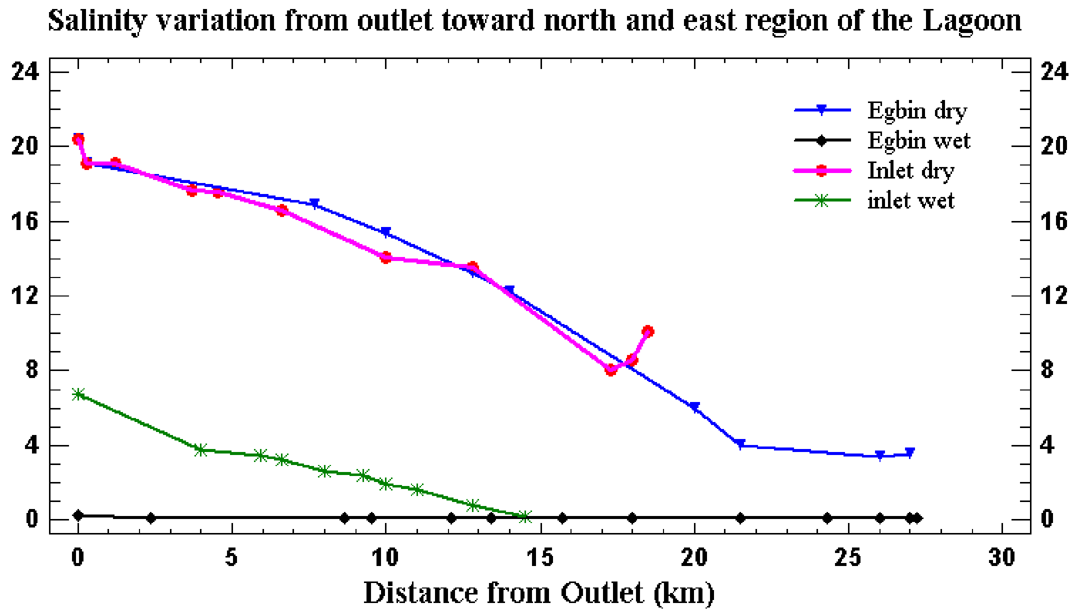


Figure 6.19: Salinity variation along two transects from the Lagoon outlet during dry and wet seasons. Blue and red line graph show the transect towards Egbin (eastern region of the Lagoon) during dry and wet season, while the green and black line graph show the transect from the outlet towards the Lagoon inlet (northern region)

6.6 Mixing/stratification process

Probing further into the investigation of the Lagoon assessment the nature of its stratification was examined using the Richardson number (Ri). The Ri is one of the important fundamental non-dimensional numbers of stratified flow which is expressed as the ratio of the buoyancy term to the flow shear term. It is the measure of stratification in any waterbody. This method was used to investigate physical processes that govern the vertical mixing/stratification in the Lagoon; this has been successfully applied to estuaries (Dyer, 1991), stably stratified turbulence (Galperin, Sukoriansky & Anderson, 2007). When converted to potential energy it has found its application in lakes and lagoons (Gale, Pattiaratchi & Ranasinghe, 2006) and commonly in coastal seas (Rippeth & Simpson, 1996). The Richardson number, (R_i), defines as the measure of the amount of turbulent kinetic energy k that is irreversibly converted to minimum potential energy that a stratified liquid can attain which cannot be converted back to kinetic energy due to turbulent mixing. The Richardson number according to the author's design in Figure 3.9 under Chapter Three, Section 3.12 was defined as:

$$R_i = \frac{{}^{-g}/_{\rho} \times {}^{\delta_\rho}/_{\delta_Z}}{({}^{\delta_\mu}/_{\delta_Z})^2}$$

Where ρ = the measure of density of water

g is acceleration due to gravity

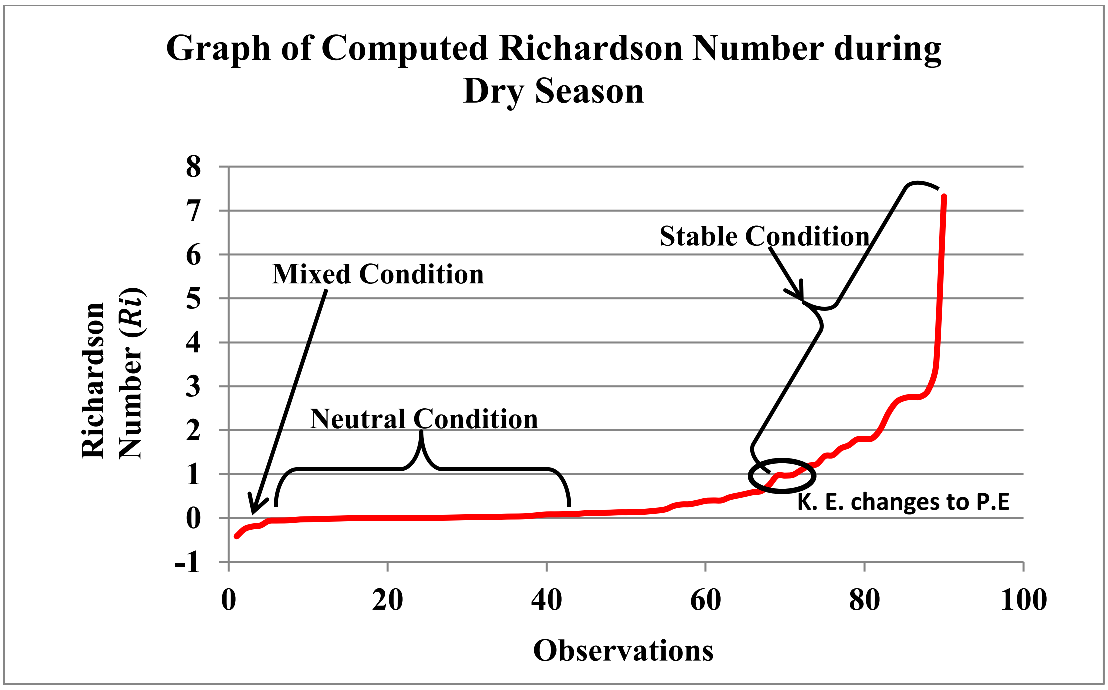
δ_ρ = Density at upper depth – density at lower depth

δ_Z = Upper depth – lower depth

Using the theoretical Richardson numbers scale ($0.05 \leq R_i \leq 1$) suggested by Dyer (1991) and Venayagamoorthy & Koseff (2016) that at low Richardson number ($R_i < 0.25$), turbulent kinetic energy grows hence mixing occurs. However, at high Richardson number($R_i > 0.25$), kinetic energy decays hence the water column is stable. The Range of Richardson value at both dry and wet seasons from the computed Ri were scaled out to identify what state of stability is the Lagoon at the two seasons of data collection. Table 6.9 gives the summary of range, lowest Ri and highest Ri of the Lagoon mixing pattern for wet and dry seasons. Figures 6.20a and 6.20b show that during the dry season the Lagoon is more stable than in the wet season because a small portion of the computed Richardson number (about 5%) in dry season is less than zero while 33% is less than zero in wet season. However, the wet season result exhibits much of vertical mixing which implies that there is sufficient turbulence to overcome density layering. The percentage ratio of the Lagoon stratification during dry season to that of wet season was computed to be approximately 1:7.

Table 6.9: Summary of the range of computed Richardson number on the Lagoon during dry and wet seasons

Season	Lowest *Ri*	Highest *Ri*	Range of *Ri*
Dry	-0.415	7.322	7.737
Wet	-15.761	19.777	35.538



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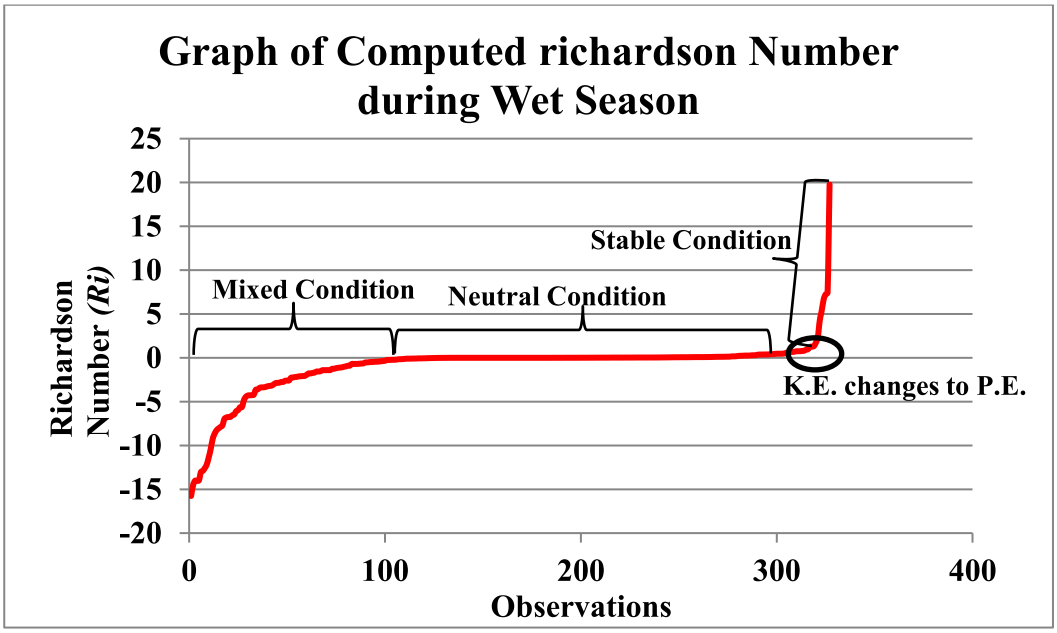


(b)

Figure 6.20: Pragmatic condition of turbulent mixing in the Lagoon showing combination of mixed condition ($Ri < 0$), neutral condition ($Ri = 0$) and stable condition($Ri > 1$). (a) Dry season scenario and (b) wet season scenario

Furthermore, the stratification profile of the Lagoon was computed using Umgiesser & Zonta, (2010) that defined Lagoon stratification as difference between the salinity at the water surface and the salinity near the bottom divided by the mean salinity at the same point. Stratification then is representation of non-dimensional parameter $\Delta S/S_o$, where ΔS is the surface to near bottom difference in salinity and S_o is the mean salinity. Based on the definition, stratification was computed for dry and wet seasons. This was plotted against average depth of each location resulting in Figures 6.21 and 6.2 which replicate stratified and mixed conditions during dry and wet seasons respectively.

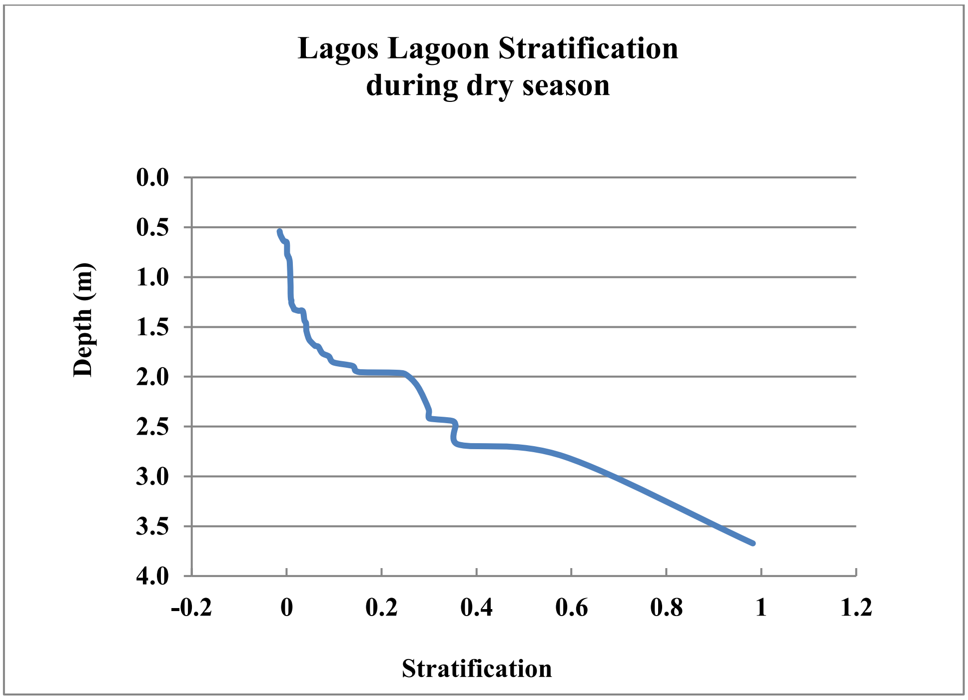


Figure 6.21: Stratification of the lagoon during the dry season exhibiting stratified mixing

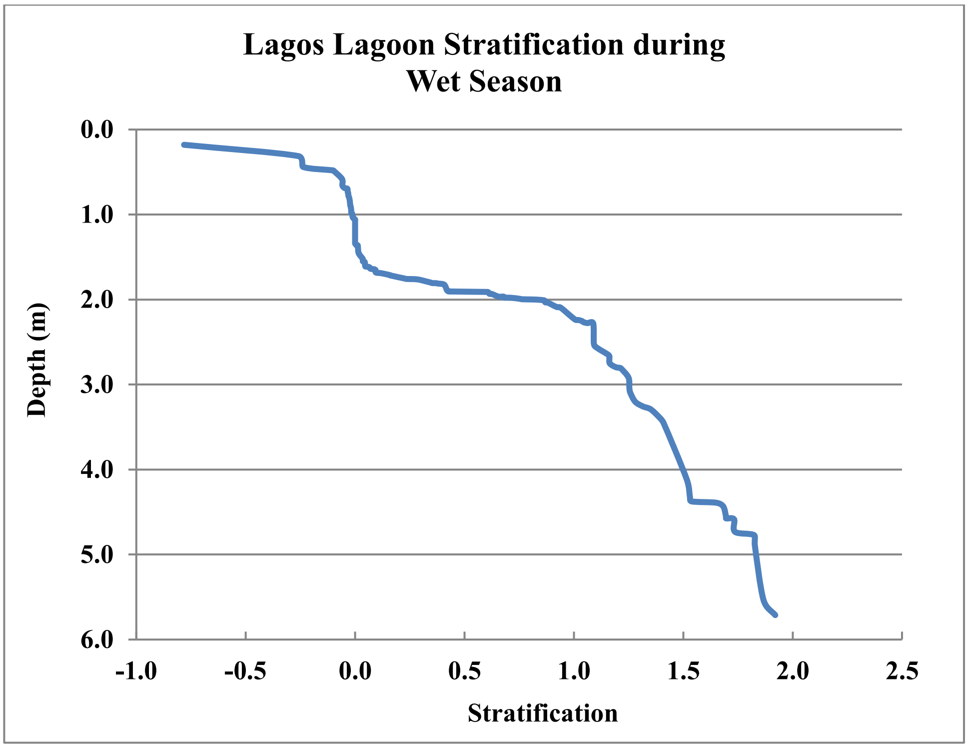


Figure 6.22: Stratification of the lagoon during the wet season exhibiting mixed condition

The structure of the two figures agreed in pattern with the different type of stratification described by Umgiesser & Zonta (2010). Figure 6.21 depicts mixed layer of the system's profile with sharp steepness in the graph along the depth profile corroborating the result obtained from Richardson computation during wet season. Small values of Richardson number indicate small buoyancy force (a uniform velocity) and dominant effect of shear, the result is mixing in the vertical profile of the Lagoon water. The range of computed Richardson values that was obtained in this research during the wet season was very small, average across the Lagoon was -0.94, indicating dominant shear force and mixing. Hence the bottom friction is larger enough to mix the entire water column, an almost vertically homogeneous water profile results.

However, during the dry season a different situation is the case. A stratified water column was the experience (Figure 6.20); it shows a gentle gradient slope as depth was plotted against stratification. Unlike during the wet season, a non-homogeneous structure was the case of the Lagoon water profile. Comparing the data for the two seasons (Figure 6.23), it was noticed that the Lagoon exhibits equal values of mixed conditions at the depth range between 1.0m and 1.5m during the wet and dry season. This implies that at whatever season of the year, the Lagoon shows a well-mixed condition at depth range between 1.0m and 1.5m. At this depth range, there may not likely be a significant variation in the stratification of the Lagoon at any spatial location. Also at this depth throughout the Lagoon it is possible that there is uniform velocity that produces high kinetic energy and dominant effect of shear; this of course is the reason for mixing conditions at this depth.

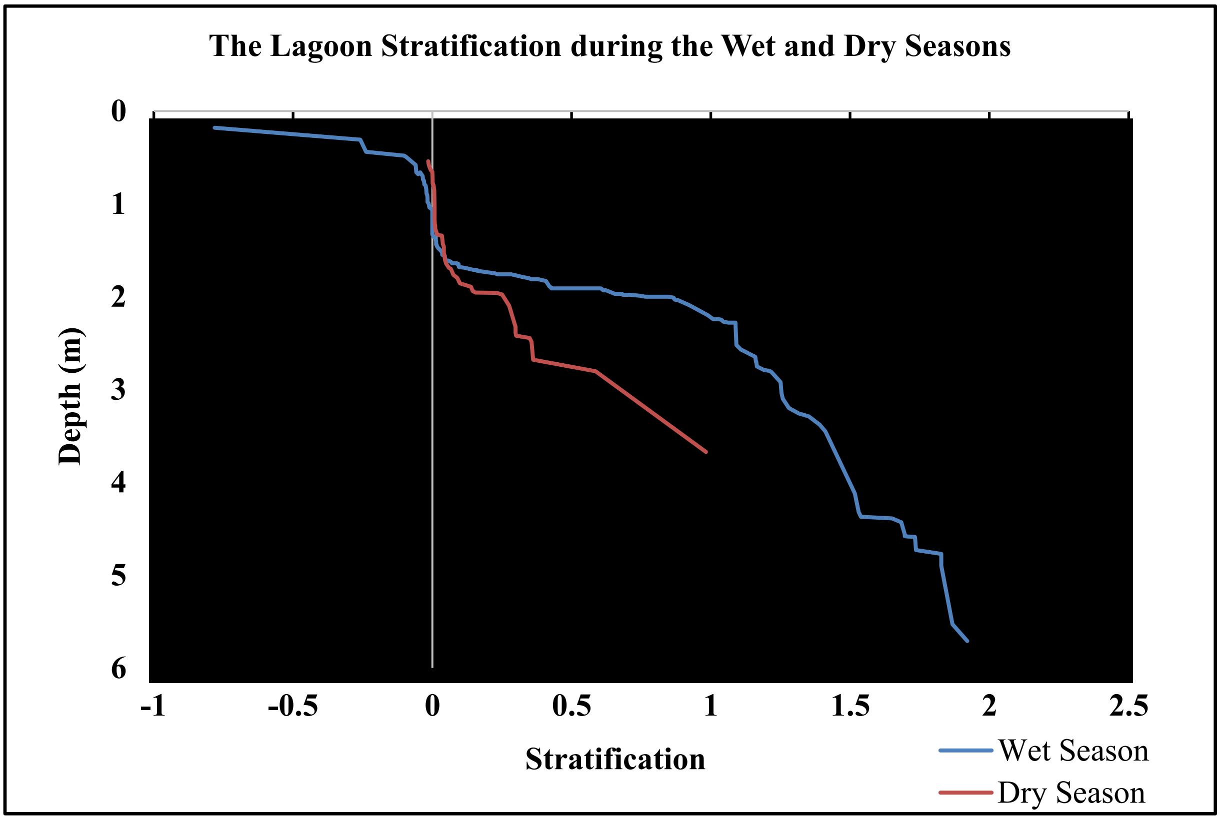


Figure 6.23: Comparative stratification of the Lagoon during the wet and dry seasons which shows equal stratification at the depth range of approximately between 1m and 1.5m. This is the depth where there is always uniform velocity and well mixing condition irrespective of the season.

6.6.1 Spatial stratification variability

Further analysis was carried out on the Lagoon stratification/mixing at six spatial locations in order to examine the mixing pattern at various locations on the Lagoon during the two prevailing seasons (wet and dry). Evident from different researchers (Dyer, 1991;

Galperin, Sukoriansky & Anderson, 2007; Grachev et al., 2013; Venayagamoorthy & Koseff, 2016) show that whenever $R_i < 0.25$ mixing occurs, hence unstable flows; $R_i = 0$ neutral flows and $R_i > 0.25$ stable flows. In line with this Richardson number threshold scaling, the result of computed R_i from six spatial locations on the Lagoon were averaged to show the type of flow and level of turbulence due to buoyancy, Table 6.10 shows the summary of the result obtained. It can be observed that at Egbin region there was neutral flow during the two seasons, however, at the Five-Cowrie area a stable flow in the dry season and a large mixing during the wet season. Conversely, the mid-region of the Lagoon showed partial mixing in both dry and wet seasons with small positive value of R_i. Moreover, at the outlet and inlet region during dry and wet seasons, the flow was partial mixing and large mixing at the outlet during the wet season. Generally, in all the locations where there is partial mixing, effect of velocity shear is dominant hence any little disturbance breaks into instabilities and provides mixing.

Table 6.10: Summary of spatial mixing/stratification pattern in the Lagos Lagoon during dry and wet season

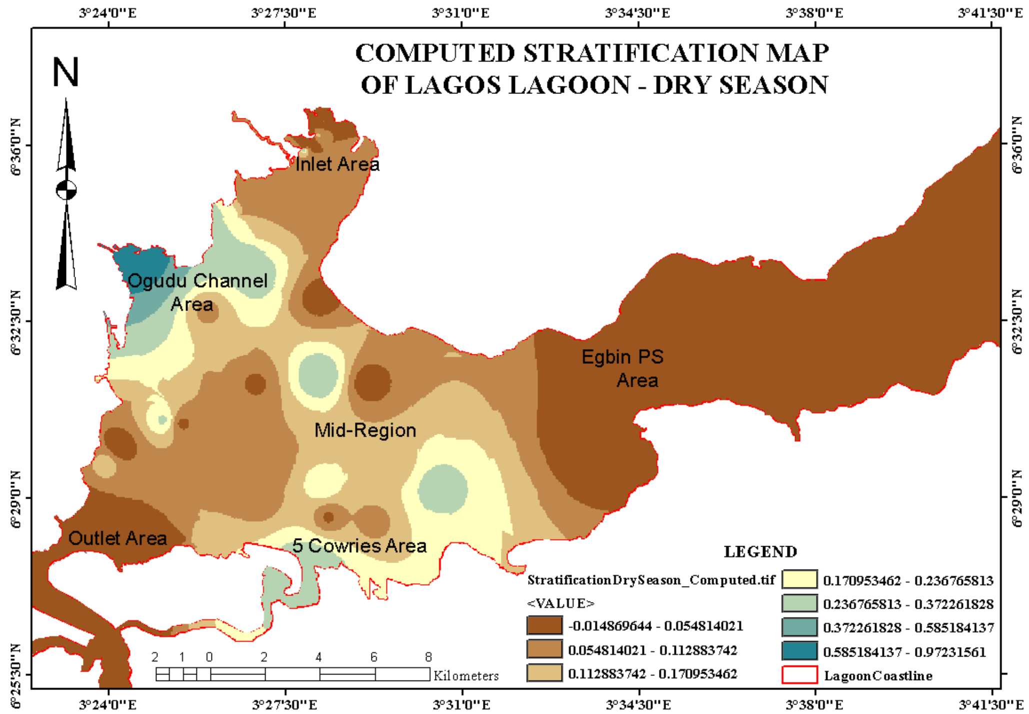
Location	Season	Average value of R_i	Type of flow	Level of turbulence due to buoyancy
Inlet	Dry	Small positive	Partial mixing	Weak stable
Outlet	Dry	Small positive	Partial mixing	Weak stable
Ogudu	Dry	Small negative	Partial mixing	Small
Five-Cowrie	Dry	Positive	Stable	Stable
Egbin	Dry	Zero	Neutral	Neutral
Mid-Region	Dry	Small positive	Partial mixing	Weak stable
Inlet	Wet	Small negative	Partial mixing	Small
Outlet	Wet	Negative	Mixed	Mixed
Ogudu	Wet	Positive	Stable	Stable
Five-Cowrie	Wet	Positive	Stable	Stable
Egbin	Wet	Zero	Neutral	Neutral
Mid-Region	Wet	Partial mixing	Partial mixing	Weak stable

6.6.2 Modelling the Lagoon stratification in GIS environment

Further to the assessment of the Lagoon salinity and stratification, the computed stratification value from Equation 3.39 Section 3.9 was plotted and then modelled in

ArcGIS. The two results of the computed and modelled were compared as depicted in Figures 6.24(a), 6.24(b), 6.25(a) and 6.25(b). The computed and model results were the same having just slight difference. Clearly illustrated in Figures 6.24 and 6.25 are the stratification condition of the Lagoon during dry and wet season, Ogudu area being the most stratified part of the Lagoon.

It was observed that during the wet season the Lagoon exhibits well-mixed condition (Figure 6.25) with high values of computed stratification dominating a major part of the data coverage in the Lagoon. On the other hand, low values of computed stratification dominated most part of the data coverage in the Lagoon during dry season. This is an indication of stable condition reflecting from the classification pattern judging from Figure 6.24. The reason for mixing condition in most part of the Lagoon during the wet season could be suggested to be influenced by the fresh water and rainfall input that is dominant in the Nigerian climate during the wet season.



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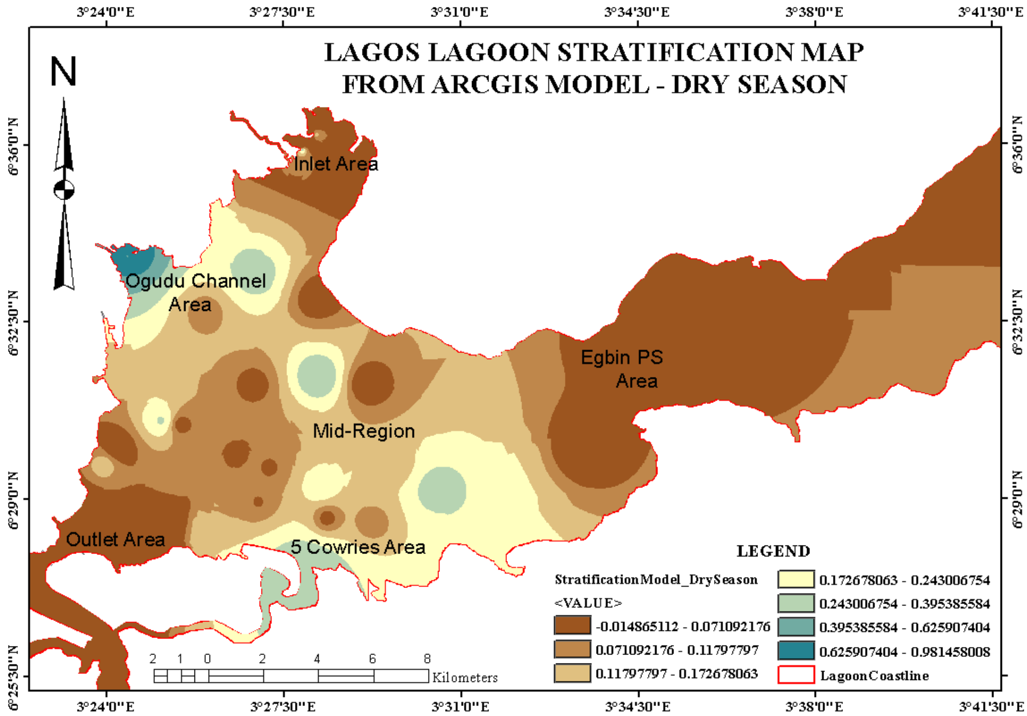
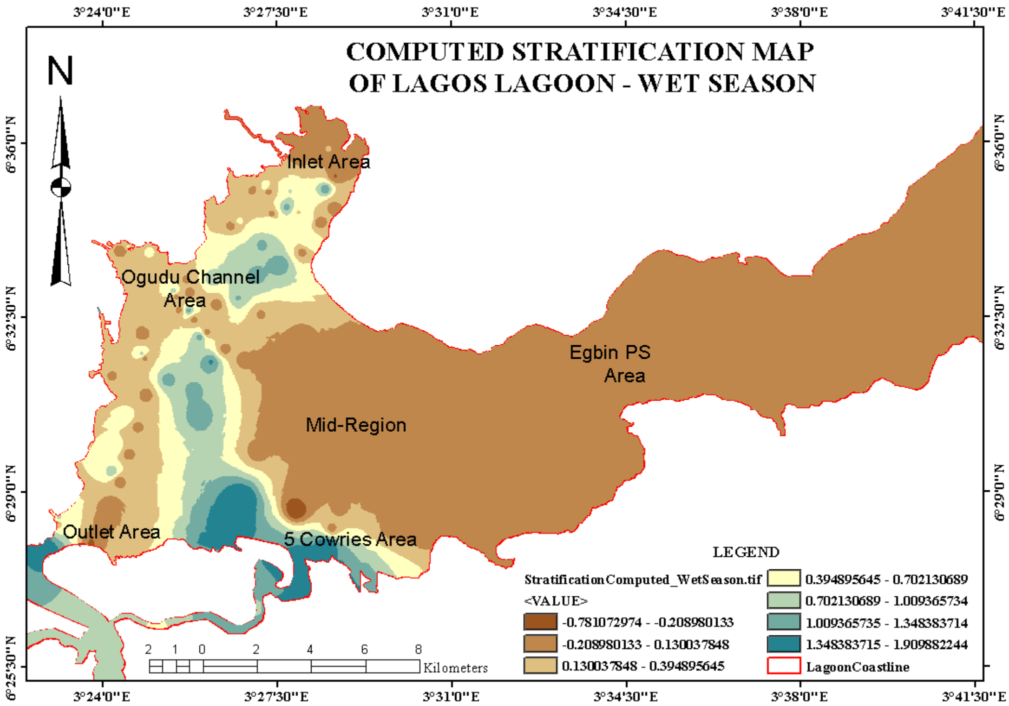


(b)

Figure 6.24: Stratification map of Lagos Lagoon during dry season, (a) Computed generated map, (b) ArcGIS model generated map. (PS inside the map means Power Station)



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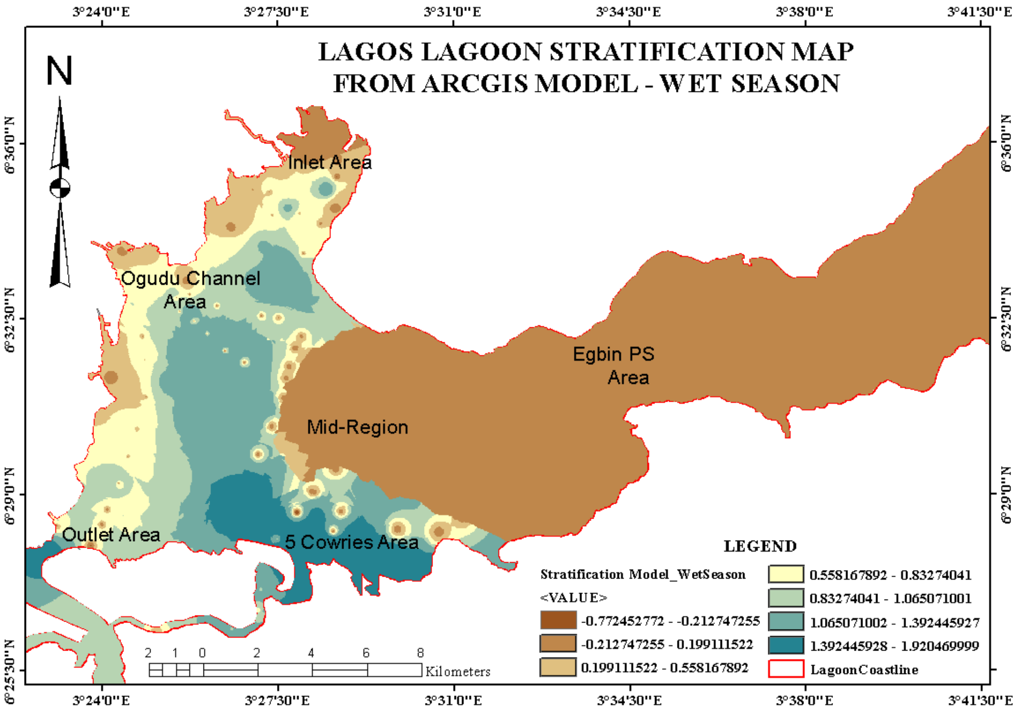


(b)

Figure 6.25: Stratification map of Lagos Lagoon during wet season, (a) Computed generated map, (b) ArcGIS model generated map

6.6.3 Cluster and outlier analysis

Cluster and outlier analysis was carried out on the computed Richardson number using the cluster and outlier analysis tool in ArcGIS. This identifies spatial clusters of features with high or low values. The tool works based on the use of Moran Index value; Moran Index value is a spatial autocorrelation tool that measures spatial autocorrelation based on feature locations and feature values simultaneously. In a set of features and associated attributes, it evaluates whether the pattern expressed is clustered, dispersed or random. A positive Index (I) indicates that a feature has neighbouring features with similar high or low attribute values, this feature is part of a cluster. However, a negative value for I indicates that the feature has neighbouring features with dissimilar values, such feature is an outlier. In either case, the p-value for the feature must be small enough for the cluster or outlier to be considered statistically significant. On the table of content layer in ArcMap, the output field is displayed as cluster of high values (HH), cluster of low values (LL), outlier in which a high value is surrounded by low values (HL), outliers in which a low value is surrounded by high values (LH), and Not significant.

To accomplish this analysis, four major steps were followed, these are:

1. Perform spatial autocorrelation Moran I so as to quickly access any kind of clustering. When the tool runs it essentially compare the distribution of feature values to hypothetical random distribution.
2. Calculate the beginning distance at which to start analysis of spatial autocorrelation and the distance to start increments.
3. Carry out incremental autocorrelation in order to measure spatial autocorrelation for a series of distances and their corresponding z-score which reflect the intensity of spatial clustering, and statistically significant peak z-scores indicate distances where spatial processes promoting clustering are most pronounced.
4. Next, the cluster and outliers analysis tool was used to identify statistically significant hot spots, cold spots and spatial outliers using the Moran's I statistics. Also, hot spot analysis tool was used so as to create new output feature class with z-score, p-value and confidence level bin for each feature in the input feature class.

Interestingly, during the wet season, the spatial statistical analysis result is summarised in Figure 6.26 which reveals varying clustered pattern of $R_i$with outlet region recording very low z-score of less than -2.58 and p-value 0.01. This implies a spatial cluster of low values of R_i, and hence the Lagoon is well mixed at this region. At Ogudu area, the result of the spatial statistics shows a cluster of high values. This is confirmed with the high z-score value (greater than 2.58) and low p-value (0.01). At this region there is stability; this is due to a small velocity shear produced by large buoyancy; kinetic energy is converted to potential energy in the entire region. The pattern at Five Cowrie reveals a stable flow. However, in the other three remaining locations, the flow could either be neutral or partial mixing, a z-score near zero which indicates no apparent spatial clustering. This is a situation where a high value is surrounded by low values (HL) or a low value surrounded by high values (LH).

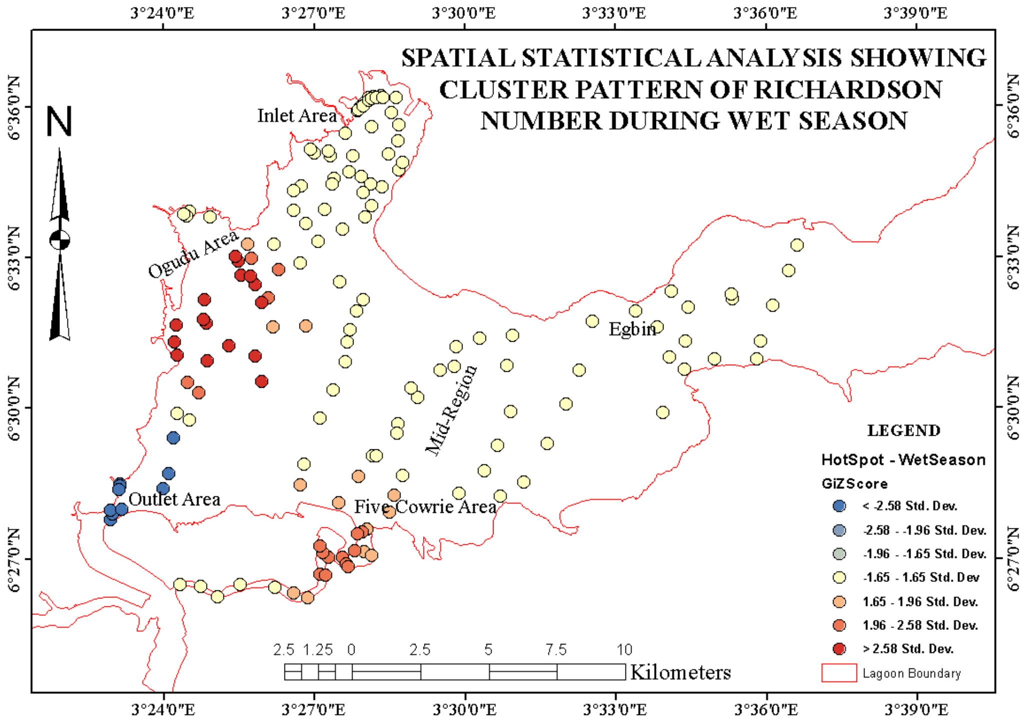


Figure 6.26: Map of spatial clustering analysis result revealing significant clustering at three of six locations on the Lagoon during the wet season.

The result from Figure 6.27 shows clustering pattern of high values of $R_i$around Five Cowries and somewhere in between Ogudu and outlet region. The implication is that these are the areas where we have the highest stability on the Lagoon using dry season dataset. The remaining locations show a pattern with no statistical significant clustering; hence flow could either be neutral or partial mixing around these areas. With the exception of a small portion in the mid-region which show mixed flow, the clustering has a significant p-value less than 0.10 (90% confidence level) with positive z-score of 1.65 – 1.96. This indicates that it is unlikely that the observed spatial pattern reflects the theoretical random pattern represented by the null hypothesis; hence reject the null hypothesis and accept the alternate hypothesis that the Richardson datasets has cluster pattern of high or low values.

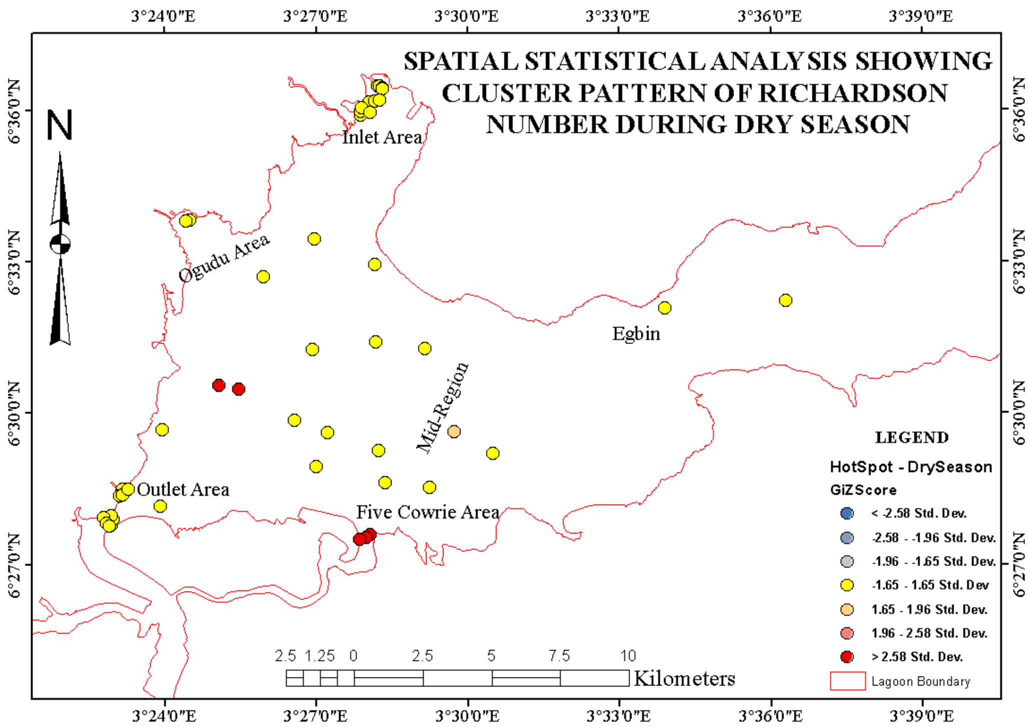


Figure 6.27: Map of spatial clustering analysis result revealing clustering at two of six locations on the Lagoon during dry season

Summarily, the clustering analysis for the wet season indicates that extrapolated values of Richardson number show more mixing and neutral flow than in the dry season. Alternatively, the dry season exhibited more stable and neutral flow. This statement support the results displayed in Figures 6.20a and b. Small buoyancy and dominant effect of shear are prevalent during the wet season hence the Lagoon is more turbulent in the wet season than the dry season.

6.6.4 Flushing time

Following the assessment of the Lagoon salinity, there is necessity to compute the flushing time of the Lagoon system since there is clear difference in its salinity variability, so as to know how long it takes the system to flush away saline water. The flushing behaviour was investigated by computing the time it took for the system to flush the saline water and replace it with fresh water intrusion from inland. First of all, the flux rate into the Lagoon through the inlets using the measured surface velocity and the cross sectional area of each of the inlets were computed. The cross sectional area was calculated using the GPS coordinates of the two ends of the inlet's mouth and the depth across it. Table 6.11 show the summary of the computed flux rate during the dry and wet seasons.

Table 6.11: Average depth and flux computed the inlets and outlet of the Lagoon during wet and dry season

	Dry Season		**Wet Season**	
Location	**Average Depth(m)**	**Flux Rate (m^3/s)**	**Average Depth (m)**	**Flux Rate (m^3/s)**
Ogun River	2.17	197.18	1.95	135.87
Majidun River	11.05	282.84	10.46	418.86
Outlet	13.50	1608.71	11.82	2942.50
Ebute Meta Channel	1.32	88.32	1.38	181.93
Ogudu	0.69	31.88	0.51	45.65

Also, fractional fresh water concentration was computed, the model for the fractional fresh water concentration was adopted from Dyer (1997), the model was defined in Equation 3.94 in chapter three. The result of the fractional fresh water in the two seasons is represented in Table 6.12; the concentration of fresh water has increased during the wet season. This implies that the Lagoon exhibits more fresh water as a result of rainfall and fresh water input.

Table 6.12: Computation of fractional fresh water concentration

Season	Fractional freshwater concentration
Dry	0.606
Wet	0.700

Finally, the computed fluxes and the fractional fresh water computed in Tables 6.11 and 6.12 were used for the computation of the flushing time for the Lagoon. Table 6.13 show the result of the computed flushing time for the Lagoon during the dry and wet seasons. It was observed that the flushing time reduced by approximately four days which is an indication that the average salinity of the Lagoon reduced during wet season. This implies that more fresh water intrude into the system due to rainfall input and possibly underground water and fresh water from upland river that emptied in the Lagoon. The flushing time changes with variations in the inlet fluxes and the rate of fractional fresh water concentration. This shows that the fractional fresh water concentration (*f*) increases from dry season to wet season by 15.65%.

Conclusively, the computed flushing time, as one of the new findings in the PhD, indicates that most of the potential pollutant or industrial effluence from the industrial area surrounding the Lagoon may be flushed from the Lagoon in the time estimated as flushing time (dry season = 26days and wet season = 22 days) of the Lagoon during dry and wet season. However, high pollutant levels can remain in pockets of stagnant water much longer. In the Lagoon, locations around Ogudu region where the local fishermen build artificial barriers to create stagnant water for fishing purpose can manifest such experience. Figure 6.28 shows the region on the Lagoon that is vulnerable to lightly stagnation because of the activities of local fishermen.

Table 6.13: Flushing time during dry and wet season

Season	Flushing Time (day)
Dry	26.07
Wet	21.99

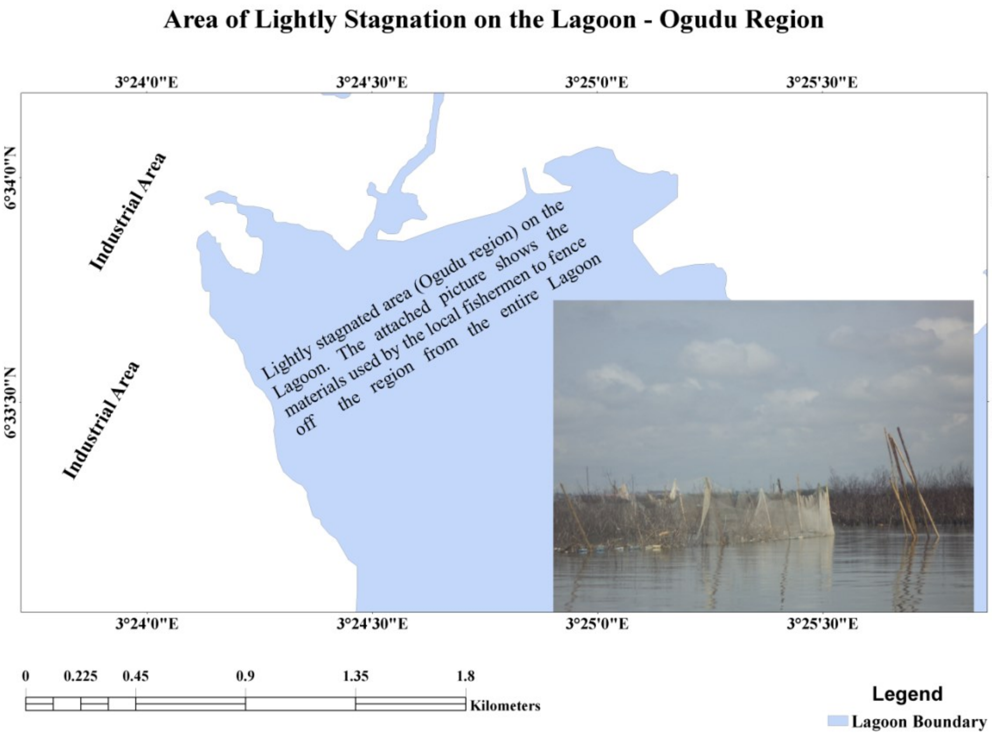


Figure 6.28: Area of lightly stagnation (Ogudu Region) on the Lagoon. The attached picture shows the materials used by the local fishermen to fence off the region from the rest of the Lagoon for the purpose of the fishing occupation

6.7 Spatio particle characterization analysis

Grain size is a basic physical property in recognising sediment deposition in any environment Poppe *et al.* (2004). There is spatial variability in bed surface sediment grain size spectra from individual depositional environments, these vary as a result of the particle size distribution (PSD) (Watson *et al*., 2013), transport processes and hydrodynamic characteristics of deposition (Friedman & Sanders, 1978).

Analysis of the PSD of sediment samples from coastal environments have been used by many scientists to detail sub-environments (Glaister & Nelson, 1974), identifying events of deposition and erosion in mudflat (low water mark) environments (Hartmann & Christiansen, 1992) and estimate relationship between tidal processes and aeolian (Greenwood, 1969).

Part of the research data collection was water and sediment samples at different locations. The samples were subjected to two different empirical tests (Andreasen Pipette and Hindered settling experiments), Andreasen pipette was used for determination of particle size distribution while the Hindered settling experiment, which is the relative settling velocity of a single particle due to interactions with neighbouring particles, was used for determining settling velocity of particle in the Lagoon.

6.7.1 Andreasen pipette experiment

The water sample collected from different spatial locations on the Lagoon was brought to the laboratory in order perform Andreasen pipette experiments (see Manning *et al., in press* for methodology). Homogeneous suspension was allowed, to settle in a cylinder, at intervals of time (0.1s, 1s, 3s, 5s, 10s, 20s and 30s) samples were taken from the settling suspension at a fixed horizontal level. Each sample contains a representative sample of the suspension, with the exception of the particle greater than a critical size, all of which will have settled below the level of the sampling point. The concentration of sediment in a sample taken at time t is determined; this concentration is expressed as a percentage. Weight of the suspended sediment derived at regular interval of time was determined with the cumulative weight (*p*) finer than particle size (*d*) (%). *P* and *d*are computed using Equations 6.6 and 6.7 respectively.

$$p_t = \frac{w_{d(t)} - w_{c(t)}}{w_{d(t=0)} - w_{c(t=0)}} * 100 \qquad 6.1$$

Where w_d = dish + dry sediment

w_c = dish weight

t = zero temperature and temperature at interval of time the measurement is taken

$$d^2 = F^2 * w_s \qquad 6.2$$

$$w_s = \frac{depth\ of sampling\ (cm)}{Elapsedtime\ (min)} \qquad 6.3$$

The d and p values from the different spatial locations on the Lagoon were plotted; this revealed the percentage of particles and particle diameter that settle at a given time. Each of the Tables 6 - A1 to A6 and Figures 6 - A1 to A6 in appendix 6 shows the cumulative sediment grain size distribution at each of the seven locations where samples were collected from the Lagoon for the empirical test of PSD. Table 6.14 shows the summary of the settling particle diameter and their respective cumulative percent at intervals in minutes. According to the Wentworth-Grain-size-chart and the International scale for grain size, the Particle Size Distribution in all the locations where samples were collected fall within fine silt and fine sand (0.01mm – 0.08mm).

Comparatively, the analysis of the PSD and settling rate of the suspended particles on the Lagoon at six locations reveals that the cumulative size of fine grain sediments that settled within 30 minutes of the experiment at the six locations was between the range of 45% and 98%. Figure 6.29 is the graphical representation of Table 6.14 which shows that population of particles size of between 10µm and 32µm constitute the main distribution in all the locations, this implies that generally the average particle size distribution on the Lagoon is mostly fine silt.

The cumulative rate of settling sediment particles was very high at three locations (the mid-region, outlet and inlet area); this falls within the cumulative range of 85% and 98%. The proportion of particles size 10µm - 30µm and particles of size 40µm - 80µm are almost the same. This implies that mixture of the sediment compositions in the three locations could be inferred from the Wentworth and international chart for sediment grain size is between medium silt and fine sand.

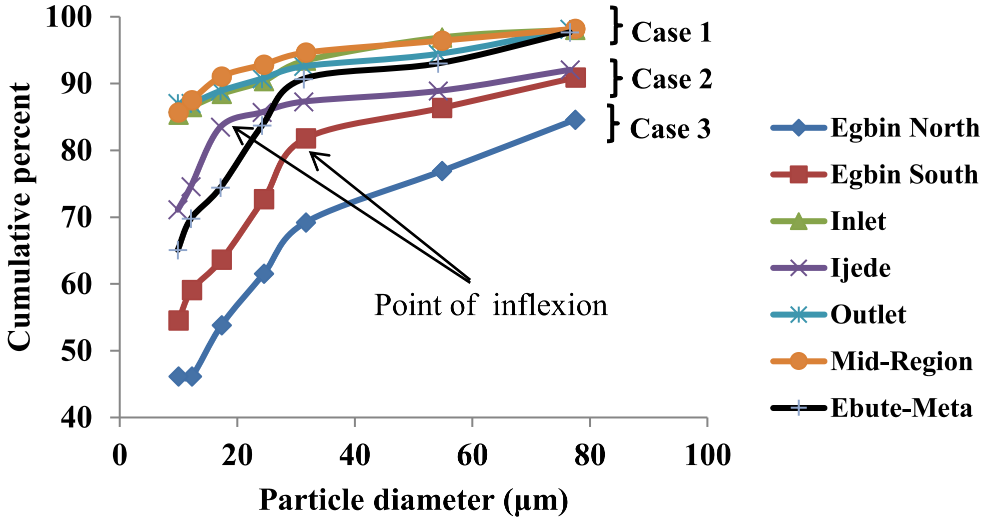


Figure 6.29: Cumulative size distribution of the fine grained sediment sample on six spatial locations on the Lagoon. Nodes on the distribution curve indicate time intervals (time increasing from right to left).

Table 6.14: Summary of the Andreasen empirical test carried out on the sample data collected from seven spatial locations

	Outlet		Ebute-Meta		Inlet		Mid-Region		Ijede		Egbin North		Egbin South	
Time (Min)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)	Particle size d (μm)	Cumulative weight (P) finer than d (%)
0	-	100	-	100	-	100	-	100	-	100	-	100	-	100
0.5	76.59	98.15	76.59	97.67	77.52	98.08	77.52	98.21	76.6	92.06	77.52	84.61	77.53	90.91
1	54.15	94.44	54.16	93.02	54.82	96.92	54.81	96.43	54.16	88.89	54.82	76.92	54.81	86.36
3	31.27	92.59	31.27	90.7	31.65	93.46	31.65	94.64	31.27	87.3	31.65	69.23	31.65	81.81
5	24.22	90.74	24.22	83.72	24.52	90.38	24.52	92.86	24.22	85.71	24.51	61.53	24.52	72.72
10	17.13	88.89	17.13	74.42	17.33	88.46	17.34	91.07	17.12	83.49	17.34	53.85	17.34	63.63
20	12.11	87.04	12.11	69.77	12.26	86.53	12.26	87.5	12.11	74.6	12.26	46.15	12.26	59.09
30	9.89	87.04	9.89	65.11	10.01	85.38	10.01	85.71	9.89	71.11	10.01	46.15	10.01	54.54

Furthermore, the rate of sediment accumulation from the PSD curves in three different locations (Ijede, Egbin South and Egbin North) was initially slow and later became fast though at different time intervals. The time interval when the sudden change occurred could be suggested as the period when the particle size at that location changes. Conversely, there was no conspicuous changing point noticed on the PSD curves of the other three locations (Mid-point, Inlet and Outlet regions). Three cases were identified in the seven locations; each of the three cases has almost the same value as their cumulative percent. The locations where samples were collected for the Andreasen empirical test is shown as plotted in the map of the Lagos Lagoon (see Figure 6.30)

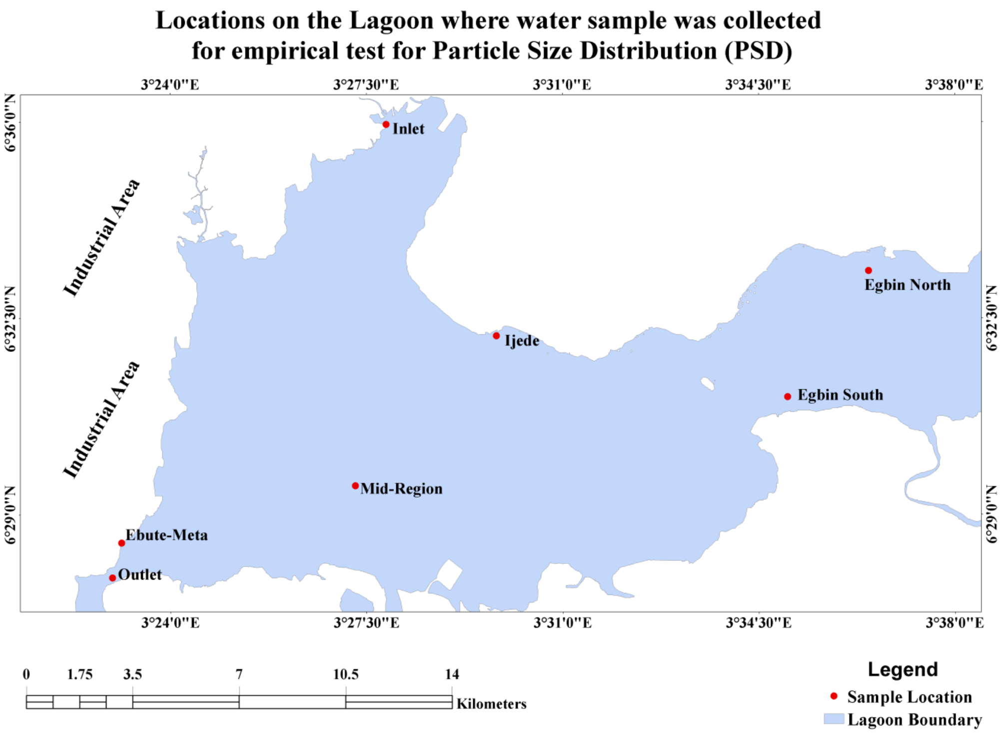


Figure 6.30: Locations on the Lagoon where water sample was collected for performing Adreasen empirical test for particle size distribution

The first case (combining Inlet, Mid-Region, Ebute-Meta and Outlet) suggested to be when settling velocity was constant with almost no point of inflection (changing point) except for Ebute-Meta that has a sharp changing point. The second case was the curves with the sharp point of inflexion where there was a visible change in the settling velocity of the particle. The third case has the lowest initial cumulative percent and also the lowest minimum cumulative percent of settling particle.

Sediment analysis based on Stokes' Law provides a convenient method for determining PSD (see Soulsby *et al.*, 2013). Stokes law (Stokes, 1851) states that:

> "A single solid (or nonporous) sphere settling in a fluid has a terminal settling velocity which is uniquely related to its diameter"

Figure 6.29 can be analysed based on the definition of Stokes Law thus: In scenario 1 where a common experience happened at the inlet, outlet and mid-region it could be suggested that settling particles along these regions reach constant terminal settling velocity, hence since the velocity is almost constant over time, the acceleration must be zero. If the acceleration is zero, the forces (gravity = buoyancy + drag) acting on the settling particles must be balanced. Conversely, in scenario 2 where there is sharp inflexion point, terminal settling velocity was not constant throughout each of the curves at Ijede, Egbin north and Egbin south. Hence since the velocity changed at a terminal point, the forces acting on the settling particles could be assumed not balanced. Generally, PSD from the seven locations on the Lagoon could be analysed thus on each of the curves: at high cumulative percent, many grains settle with large Reynold number, hence settling velocity increased with increase grain density and fast laminar flow. However, at low cumulative percent, few grains settle with small Reynolds number, hence settling velocity decreased with decrease grain density and slow laminar flow.

In scenario 1, the cumulative percent of settling particle was very high; this is an indication of abundance of so many macroflocs (see Manning and Dyer, 2007) or macro-sediment. In accordance with the result of Manning *et al.* (2010), with the macro-sediments encompassing approximately 85% - 98% cumulative percent of the sediment around these regions, it could be translated that the fast settling macro-sediments in the regions constitute high rate of settling velocity compared to scenarios 2 and 3 where PSD cumulative percent come as low as between 45% - 55%.

However, the settling velocity of the suspended particles in the Lagoon water was considered a phenomenon that must be known because the lower the settling velocity the smaller the particle size and the cloudy such water-body that contains the suspended particles. This leads to carrying out another empirical test where the settling velocity of the particle size in the system was determined. The principle used for the determination of the settling velocity is Hindered settling experiment; the result is discussed in section 6.7.2.

6.7.2 Hindered settling experiment

Micro-sediments rarely settle as individual particles. At high concentrations of the particle the settling particles start to hinder each other in their movements (Winterwerp, 2002), a process generally known as hindered settling (see Spearman and Manning, *in press*). As flocs grow in size usually their settling velocities continue to increase as a result of Stokes' Law relationship, but their effective density tends to decrease (Dyer & Manning, 1999). Sediment samples were collected at three of the spatial locations mentioned in section 6.7.1 and at two other locations (Ogudu and Ebute Meta). From the samples at these locations, a hindered settling experiment (see Manning *et al.,* in press for details of the methodology) was performed in order to determine the speed at which the particles settle at various locations on the Lagoon. Certain concentrations of the sample from each location were measured inside a clear cylindrical jar. The concentration of each sample was mixed with water; the initial height of the water column h_0 was also recorded with the bed layer if apparent. Each solution was shaken up and a stopwatch was started in order to record settling time of the particles. The elevation ($_h$) of the interface falling from the surface as well as the one rising from the bed (if present) was recorded as a function of time (t). 1 minute intervals were used until 15 minutes and then 2 minutes intervals.

From the result of the experiment, heights were plotted against time for all columns. The settling velocity of the interface for each column was estimated by linear regression. Figure 6.30 shows the plot of interface height against time with linear regression for spatial locations where samples were collected on the Lagoon. Table 6.16 shows the summary of settling velocity estimates based on linear regression analysis for each of the spatial locations. The Table also contains the equations and R^2 values depicted in bold. The average settling velocity for a particular plot at any location and at a given time is equivalent to:

$$Settling\ Velocity = \left(\frac{height\ at\ time\ 1 - original\ height}{time\ required\ to\ reach\ current\ height}\right) \qquad 6.4$$

Generally, it could be judged from the result of Figure 6.31 that even though settling velocities at each of the locations originates from almost the same value, after some time there was divergence in the recorded values of settling velocities from each locations, this implies that particle densities varied significantly in all the locations.

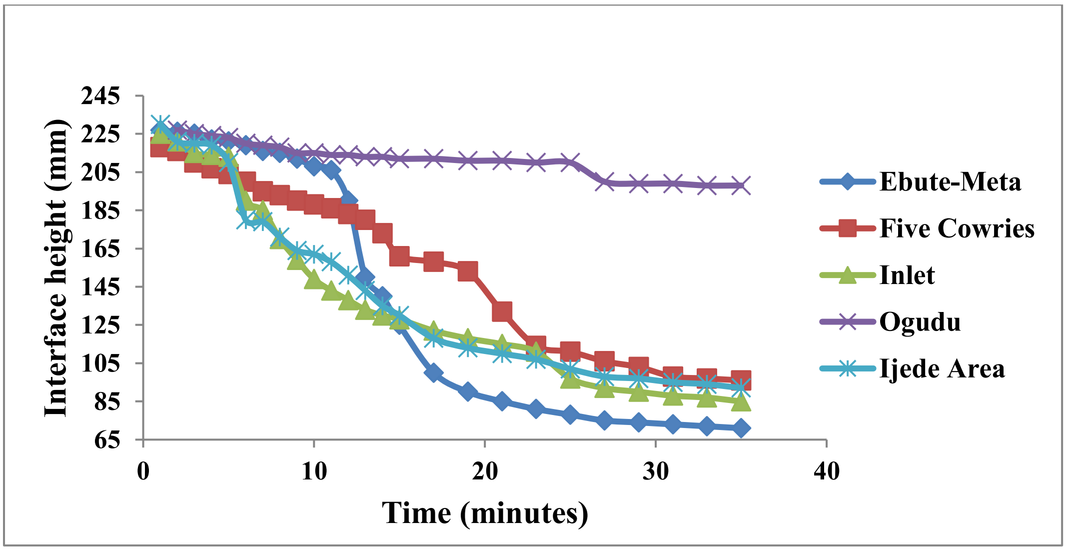


Figure 6.31: Plots of interface height against time for the five spatial locations where samples were collected on the Lagoon

Table 6.15: Summary of velocity estimates (based on linear regression analysis) for each of the plot generated for each spatial location. (The settling velocities printed bold and asterisked is the location with huge mud deposit)

Location	Settling Velocity of interface (mms^{-1})	Regression equation	R^2
Ebute Meta	0.100	Y = 0.100x - 242.86	0.882
Five Cowries	0.070	Y = 0.070x - 225.00	0.975
Inlet	0.072	Y = 0.072x - 210.01	0.884
Ogudu	**0.014***	Y = 0.014x - 224.76	0.932
Ijede Area	0.070	Y = 0.070x - 211.76	0.882

It was observed that one location (Ogudu) an experienced extremely low settling velocity. This implies that the settling particles at this location are far smaller than what is obtained in the remaining locations. The indication is that grain density of the settling particles at these two locations is very small hence a decrease in the settling velocity. This result is supported by Stokes' Law and Dyer & Manning (1999). They identify particles of highly effective density with high settling velocity and particles with lower densities are associated with low settling velocities. In agreement with Wentworth grain size chart (Appendix 6 Table 6 – A7), it could be confirmed from the results from Table 6.15 and Figure 6.31 that the settling particles at Ebute-Meta region are fine silt (0.1mm/s). However, the settling particles at Ogudu are confirmed from the Wentworth chart to be very fine silt. On-site verification during the research field work also confirms that the entire Ogudu region is filled with mud to an extent that up to about 4 km from the Ogudu channel into the Lagoon, navigation through a vessel of the smallest draft was not possible.

In conclusion, the investigation into the Lagoon spatio-particle characterization reveals that the Ogudu region consists of mud particles (very fine silt) with a very low settling velocity of 0.014mm/s; this has been the reason why the nature of the Lagoon water in this region looks more of suspension than clear water. According to Stokes' Law, the settling particles in the Lagoon (with the assumption that they are spherical in shape) have varying settling velocities that are uniquely related to the diameter of the particles at the various spatial locations. The investigation has revealed that the sediment in the Ogudu region has the smallest settling velocity of 0.014mm/s. This implies that the particles in this region are very small, and hence, the slow rate at which particles in the region settles suggests a correlation between the suspension nature of the Lagoon at the region and the settling rate. Lastly, the section has been able to achieve part of the third objective of the research “to examining the spatial characterisation of the settling particles in the Lagoon system”.

6.8 Mathematical models for lagoon marsh development

Marsh growth in coastal barrier lagoons is governed by sea-level fluctuation, sediment input and the previous character of the lagoon floor (Oertel & Woo, 1994). The preservation of a coastal area characterised with marshes (seasonally waterlogged area in wet seasons or at high tide) is a function of the degree of effect of the relative rate of sea-level rise with respect to the rate of sediment accumulation on marsh surfaces (Oertel & Woo, 1994). The group of plants and other organisms found in the tidal areas of the coastal lagoons are controlled by the fact that such plants and organisms are very resistant to salt spray, recurrent submergence (Oertel & Woo, 1994), strong winds and can condone insufficient or soft soils (Tyler & Zieman, 1999).

This section presents the various results of the models that were developed to assess marsh sediment accretion and the effect of sea level rise to the morphological structure of the case study area in case there is sudden upshot in the global sea level rise. The very first result deals with the marsh in equilibrium with mean sea level where the rate of change of marsh elevation is equal to the long-term rate of change in sea level. Introducing a dimensional homogeneity with Morris *et al.* (2002) was what makes the development of this model novel and different from Morris’ model. The assumption, in this case, is that the exponential proportionality m=1 and n vary. The rate of change of marsh elevation in the Lagoon ecosystem especially in the marsh dominated regions is assumed to be equal to the rate of change in sea level.

The model results of the rate of change of sediment elevation in relation to the marsh accretion especially in regions that are highly susceptible to mud in the Lagoon ecosystem are displayed both for the dry and wet season in Figure 6.32– 6.35. This model reveals that the rate of change of sediment elevation is increasing with marsh growth in the ecosystem of the Lagoon; hence if there is any sudden increase in the global sea level rise that impacts on the adjacent sea, this will in turn influence the rate of change of sediment elevation around the Lagoon ecosystem. The exponential functions (m and n) arise as a result that the rate of sediment accretion may either grow or decays at a rate proportional to its current value. It models a relationship in which a constant change in the independent variables (salinity, and velocity flow) give the same proportional change (that is, a percentage increase or decrease) in the dependent variable (marsh depth). Average values of salinity, density and the velocity flow of the datasets collected during the dry and wet seasons were then taken and used as the input for the independent variables for this model so as to compute the rate of change of sediment accretion. Figures 6.32 – 6.35 show the result of the model when the exponential proportionality is constant and when it varies with respect to the changes in the values of the independent variables during the dry and wet seasons. Contrasting the rate of change of sediment accretion, the model results reveal that the rate of change of sediment accretion around the Lagoon ecosystem reduces during the wet season. This implies that some of the particles are eroded away rather than settling, hence a reduction in the rate of sediment accretion.

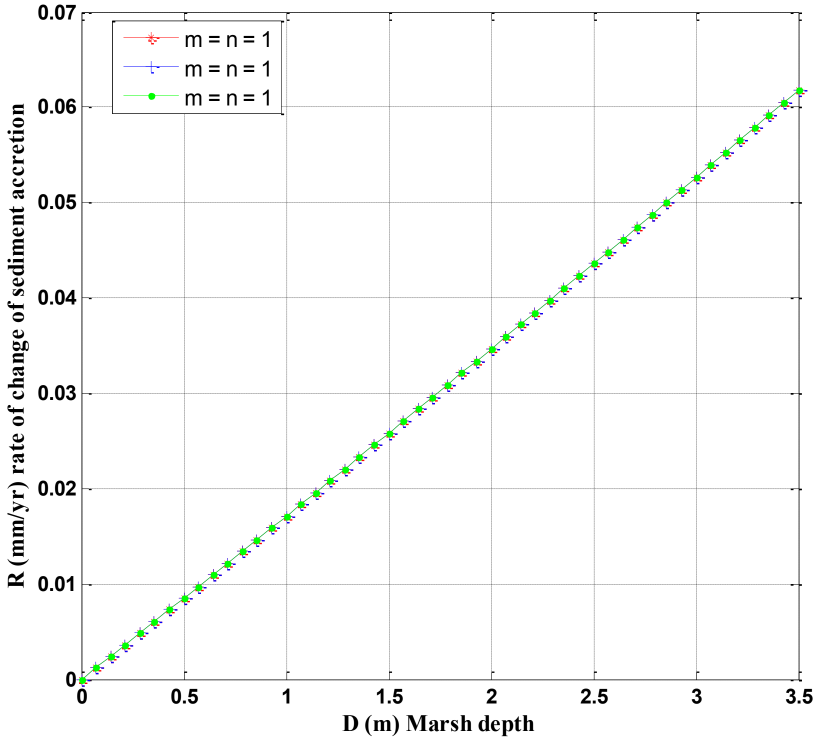


Figure 6.32: Rate of change of sediment accretion during the dry season with equal exponential proportionality in the model equation

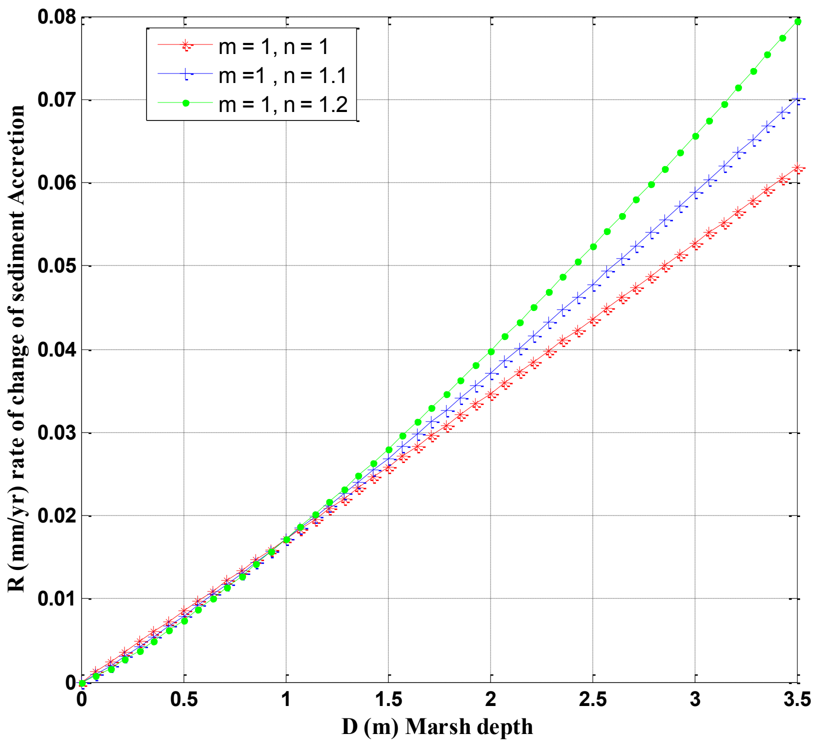


Figure 6.33: Rate of change of sediment accretion during the dry season with varying exponential proportionality in the model equation

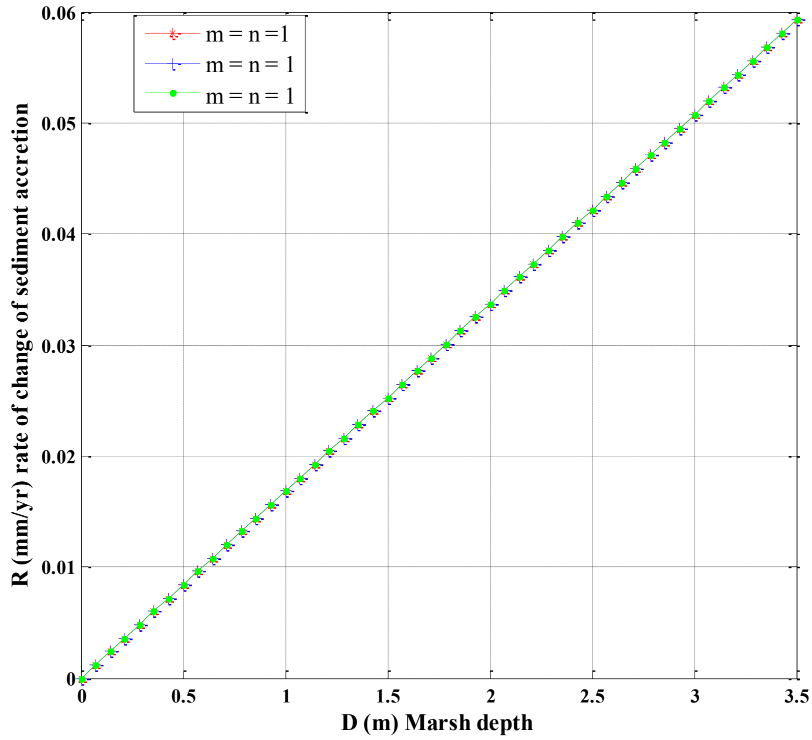


Figure 6.34: Rate of change of sediment accretion during the wet season with equal exponential proportionality in the model equation

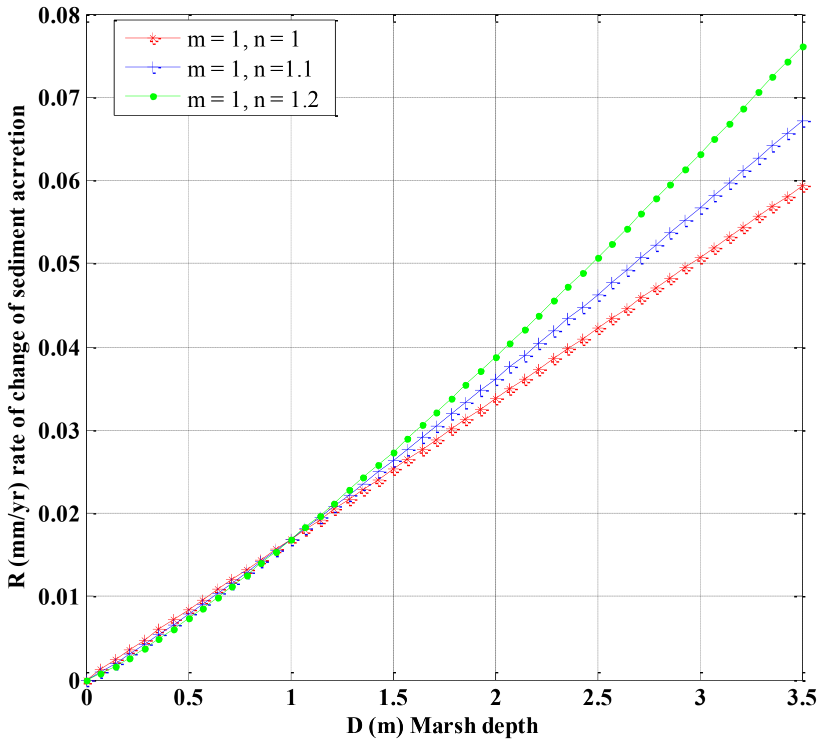


Figure 6.35: Rate of change of sediment accretion during the wet season with varying exponential proportionality in the model equation

Assuming that the long-term sea level is rising at a linear rate over time, if a linear variable is introduced to the Equation of the model, the rate of change of sediment elevation is computed and compared with equilibrium depth. In the wetland region around the Lagoon, a baseline beacon could be established with graduation marks to which the sediment deposition could be measured from time to time. The model has shown that at higher depths the rate of sediment increase is very low. This implies that at the starting point of measurement, sediment accumulation is low and the rate is considered to be slower than the rate of deposition at a more shallow depth. It could be observed that the lower the depth the higher the rate of change of sediment elevation. Figures 6.36 and 6.37 show the model results of the rate of change of sediment elevation against equilibrium depth during the dry and wet seasons. It could be observed that the rate of change of sediment elevation was 1mm/year at the depth of 5.5m during the wet season but the same rate was at the depth of 1.5m during the dry season. This implies that during the dry season, the rate of sediment elevation is conspicuous at a lower depth while the same rate is not noticed during the wet season until at a higher depth.

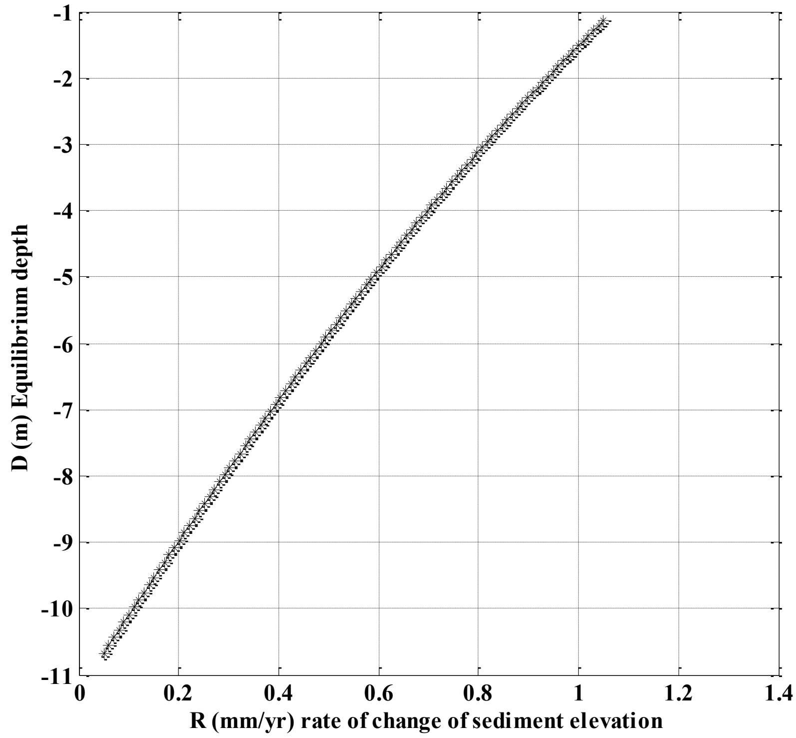


Figure 6.36: Rate of change of sediment elevation against equilibrium depth during the dry season

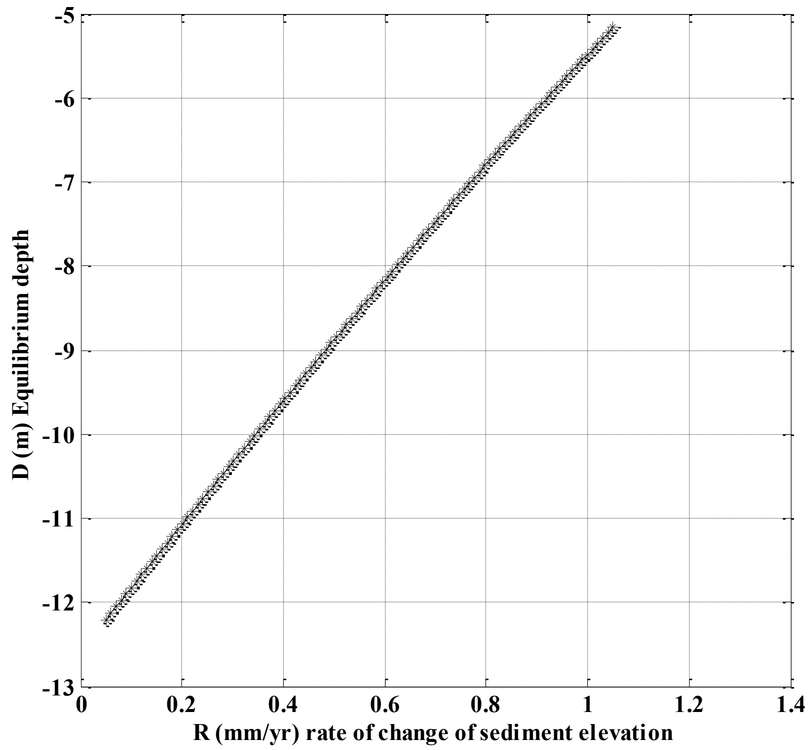
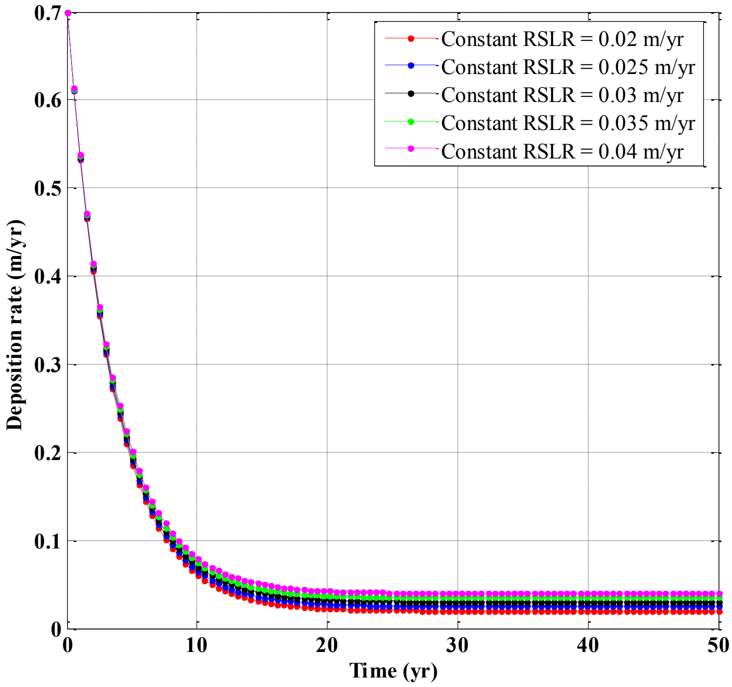
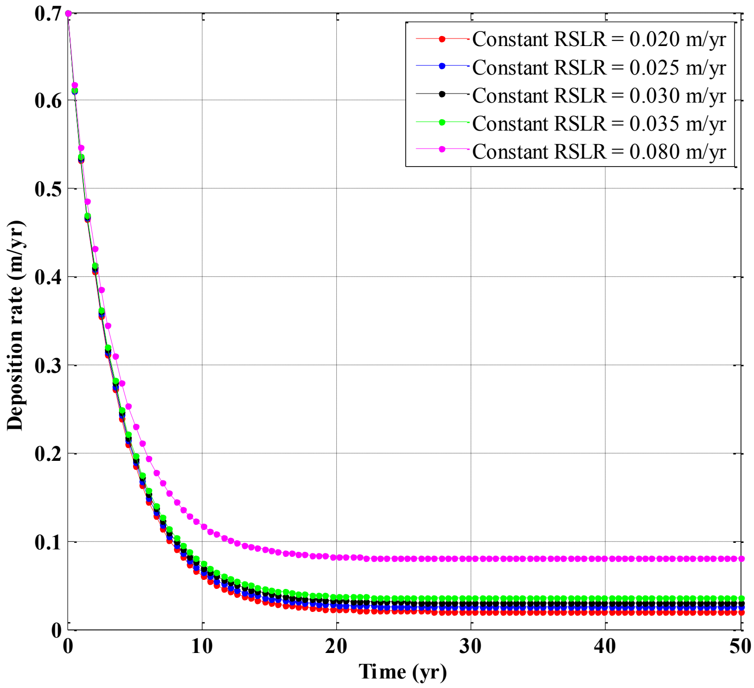


Figure 6.37: Rate of change of sediment elevation against equilibrium depth during the wet season

Furthermore, the effect that the relative sea level rise could have on the Lagoon environment in either the wet or dry seasons was modelled; the result is displayed in Figure 6.38. In the model, it is assumed that the sea level rises at different rates per year (0.02m, 0.025m, 0.03m, 0.035m and 0.04m). The model shows a decrease in the rate of sediment deposition as time in year increases; at about 18 years a constant rate of change is maintained. Even though the influence of the different rate of sea level rise applied does not give a very significant difference yet, the 0.04m/year rate still depicts the highest rate of deposition especially at the period of a constant rate of deposition, that is, from the time after 10 years. Assuming the last rate of sea level rose suddenly rise to 0.08m (Figure 6.38b), the result in the model shows that the rate of deposition will be raised also. This suggests that the entire ecosystem of the Lagoon will be subjected to a high risk of sediment deposition which would make the entire ecosystem vulnerable to flooding and pollution. As the global sea level is increasing the influence will impact an increase in deposition rate around the Lagoon ecosystem, this is very dangerous for the Lagoon ecosystem.



(a)



(b)

Figure 6.38: Predicted rate of sediment deposition with time in year, assuming a constant rate of change of sea level rise scenario. (a) This shows the rate of sediment deposition if there is no sudden geometric rise in sea level variation. (b) It depicts the deposition rate that will be experienced as a result of a sudden high increase in the sea level rise

6.9 Summary

This chapter presents further results of the assessments of morphodynamic investigations in the Lagoon. It starts by presenting the findings obtained from the assessment of the Lagoon salinity, and then the results of the salinity pattern at different spatial locations. The nature of the Lagoon salinity revealed a wide variation between its salinity during the wet and dry seasons. The wet season exhibits very low salinity and the dry season high salinity. This implies that the Lagoon is brackish during the dry season and fresh water during the dry season.

Then in more detail, the temperature against salinity regime was examined. The result shows an interfacial dynamic point where convergence takes place (approximately 30ºC; 27‰ during dry season and 28.8ºC; 26‰ for wet season). Further investigation on the Lagoon mixing and stratification shows a result of a non-homogenous layer during the wet season because of general high values of Richardson number. However, the dry season result indicates a homogenous layer condition with low values of Richardson number. Using the Richardson number at six locations on the Lagoon to perform spatial statistics analysis, the result shows clusters of high Richardson number at two different regions; this indicates high potential energy, non-uniform velocity and non-homogenous Lagoon water layer. Contrarily, the cluster analysis result during the dry season show a cluster of low Richardson number, this implies high kinetic energy, uniform velocity and homogenous water layer, hence the Lagoon water experience mixing conditions. Furthermore, the computed flushing time of the Lagoon shows a result approximately 26 and 22 days flushing time during the dry and wet seasons respectively.

At seven different locations on the Lagoon, detailed examination of its sediment characterizations were considered, and the results were displayed in two different parts. The PSD on the Lagoon revealed three scenarios: first was where cumulative percentage of settling particles was very high, with an implication that many grains settle with a large Reynold number and fast laminar flow (at the inlet, outlet and mid-region), followed by the scenario where there was a sharp inflexion, the force controlling settling particles is assumed not balanced. This experience was common to Ijede, and and Egbin south. Last is the scenario of low cumulative percent where few grains settle with small Reynold number, hence settling velocity decreased with decreased grain density and the outcome is slow laminar flow. This result is peculiar to Egbin north. Lastly, a mathematical model developed for lagoon marsh revealed that a global increase will support an increased deposition rate, high risk of flooding and pollution in the entire ecosystem.

6.10 Conclusion

This section summarises the results of the various hydrodynamic changes in the Lagoon system. Various methods used in investigating the hydrodynamic changes in the Lagoon have revealed different results that show general, spatial and seasonal changes. The assessment of the Lagoon salinity pattern reveals a wide range of salinity variations between the dry and wet seasons with low salinity values in the wet season and high salinity for the dry season. The lagoon is a fresh water entity during the wet season and brackish water in dry season. Spatio-temporal analysis confirmed this with a result of the prevalence of change of water mass in the wet season. This shows low salinity values, confirmed from low values of Richardson number. The statistical tests show that 0.48% of the variability in observations related to HW depends on the time of observation; hence the salinity variation during the wet season over a large spatial range on the Lagoon might not be noticed. The salinity of the Lagoon to a large extent is uniform. But during the dry season, 27.73% of the Lagoon variability in observations related to HW depends on time, hence it could be inferred that salinity varies spatially with time and tidal band on the Lagoon.

Furthermore, the study used Temperature-Salinity diagram analysis and the analysis reveals interfacial dynamics point where convergence takes place. This point was found to be ≥25°C in the result of Zhu *et al* (1992). In this research the two values of these points during the dry and wet seasons are approximately 30°C; 27‰ and 28.8°C;26.9‰ respectively. However, temporal daily variation of the Lagoon temperature and salinity indicates that at flood tide during the dry season salinity decreases until the HW tide and increases at ebb tide. However, temperature increases until the HW tide before it starts decreasing.

In terms of mixing/stratification in the Lagoon, there is a mixture of the type of flow on the system. The computed average value of the Richardson number is low in the wet season and hence exhibition of vertical mixing conditions where the effects of velocity shear is dominant. Consequently, this implies that sufficient turbulence is produced to overcome density layering. This shows that any little disturbance breaks into instabilities. In contrast, the average Richardson value was high during the dry season. This results in a large buoyancy force and small velocity shear; hence, the system is more stable during this season. Correspondingly, clustering analysis for the wet season indicates that extrapolated values of Richardson Number show more mixing and neutral flow than in the dry season. Alternatively, the dry season exhibited more stable and neutral flow. Small buoyancy and dominant effects of shear are prevalent during the wet season and hence the Lagoon is more turbulent in the wet season than the dry season.

Additionally, computed flushing time indicates that most of the potential pollutant or industrial effluent from the industrial area surrounding the Lagoon may be flushed from the Lagoon in the time estimated as flushing time (dry season = 26 days and wet season = 22 days) of the Lagoon during the dry and wet seasons. However, high pollutant levels can remain in pockets of stagnant water much longer. In the Lagoon, locations around the

Ogudu region where the local fishermen build artificial barriers to create stagnant water for the fishing purpose can manifest such experiences.

The investigation into the lagoon spatio-particle characterisation unveils the Ogudu region of the Lagoon dominated with mud because of the prevailing settling velocity of particles in the region. Hence, there is correlation between present shallowness of the region and the settling velocity rate.

Lastly, this chapter has been able to achieve part of the research objectives (objectives two and three) which investigate behaviour and relationship pattern of the Lagoon hydrodynamic and the spatial characterisation of the settling particles in the system.

CHAPTER SEVEN
GENERAL DISCUSSION

7.1 Introduction

Morphodynamic evolution of coastal regions especially the coastal lagoons as focused in this research and the impacts upon marine ecosystem is a wide ranging research as demonstrated in the various results and inferences from this study. Hence this chapter discusses the basic limitation of the research, the problems encountered, a review of programming and analysis tools, and comparison of the research results and inferences that justify the results achieved.

This research set out to investigate the morphodynamics of the Lagos Lagoon. From the literature (within chapter 2), Lagos Lagoon is one of the largest lagoons in West Africa and contributes to the economic growth of the region. The Lagoon is the major repository for the industrial effluence where all the effluent from the industrial locations in Lagos is deposited. More also, the naturally interconnected system of the Lagoon has been compromised with urban growth; this is believed to have influenced the morphological and hydrodynamic patterns of the system. With this motivation, a Nigerian-focused methodology was designed to use a functional mechanism to evaluate and analyse the changes in the Lagoon and its catchment area (Chapter Three). However, the major problems encountered during the execution of this study are enumerated in this Chapter. The spatial extent of the wetland system in the Lagoon was mapped, and the influence of an incessant increase in population around the Lagoon and the consequential changes in the lagoon ecosystem were detected (Chapter Four). The dynamics of the Lagoon waterbed were investigated and evaluated, exploring a comparative analysis of repeated bathymetric surveys. The results visualised the spatial distribution of accretion and erosion on the system’s waterbed (Chapter Five). Chapter Six of the thesis produced the various assessments of the Lagoon hydrodynamics with the use of the field data collected during the dominant seasons in the region.

7.2 Limitation of the research

The focus of the study, the Lagos Lagoon, covers a large area in the western region of the Nigeria's coastline. The surface area is approximately 208km^2 according to Balogun *et al.* (2011), a large area over which to gather high-resolution data. This constrained the study to the western region of the Lagoon, which has proximity to the most significant regions of social development. With the new observations, this study has developed a baseline theory for morphology and hydrodynamics on the Lagoon.

Furthermore, the research did not use existing numerical hydrodynamic models due to lack of existing hydrodynamic data this being a basic parameter for implementing a model. Hence, Any existing numerical model are not part of the functional method used in this research.

7.3 General problem

There are many problems encountered in the course of carrying out this study, major among which is data availability. The data used in any research work helps to discover answers to the outstanding question in the research area and could also predict future outcomes, hence results and methods in any research study are the direct functions of the data used (available and observed). To the best knowledge of the author, there were no data as regards hydrodynamic studies in the system; hence observed data from the field of study was designed to acquire sufficient data for the study.

In the design of the type of data for studying the morphological changes along the Lagoon coastline and around its ecosystem, Landsat data was considered for use, however the scan-line corrector (SLC) for the ETM+ sensor, onboard the Landsat 7 satellite failed permanently on the 31st May 2003 and without a working SLC, images have wedgeshaped gaps that range from a single pixel to about 12 pixels towards the edges of the scene. The outcome of the failed SLC hindered the use of the Landsat 7 ETM+ data (Chen *et al.*, 2012). This limited the number of images that could be used for the research.

Further, Landsat image data for this research covers only the dry season out of the two prevailing seasons in Nigeria. The available data that covers the wet season in the United States Geological Survey (USGS) archive were all obscured by cloud cover, and so could not be used. There are other image data that have better resolution that are more appropriate for use in the study, examples being SPOT 6 and 7 images – 1.5m resolution (Wald *et al.,* 1997), IKONOS – 1-2m resolution (Saito *et al*., 2004; Sohn & Dowman, 2001), QuikBird, EROS, and OrbView – 1-2m resolution (Saito *et al.*, 2004). However, their high cost prevented the author from obtaining such images.

The logistics of collecting data on the site posted serious problem because of domestic security challenges across Nigeria at the time of the study. The Lagoon is vulnerable to pirate activities because of oil bunkers at the extreme south-western and north-western parts of the Lagoon. The safety of people carrying out research is not guaranteed.

7.4 Programming and analysis tools

The study used ArcGIS 10.1 as a modelling tool and MATLAB as a programming tool. MATLAB code was written for the processing of Landsat images. ArcGIS 10.1 was used to build a model for the investigation of the Lagoon coastline changes, however, the various GIS-derived results from the study were the output of existing model built in ArcGIS. ENVI 5.0 combined with the ArcGIS 10.1 was used for the processing of other Landsat images used for mapping spatial variability in the Lagoon ecosystem (Chapter Four). A further instance of the use of ArcGIS 10.1 was in the clustering analysis of Richardson number computation for deriving mixing/stratification.

The various analyses in the research were carried out with the use of some software among which are Statgraphics Centurion XVI, SigmaPlot 13.0, Excel 2010 and ArcGIS 10.1.

7.5 Comparisons with the literature

7.5.1 Lagoon ecosystem variability

The results of the spatial variabilities in the Lagoon ecosystem detailed in Chapter Four were aimed at investigating the morphological changes experienced so far within the wetlands surrounding the Lagoon and whether the unabated increase in population growth and urban development have a correlation with the wetland changes. Through the investigation, it was found that the mangrove in the ecosystem has declined from 287.60km^2 to 120.58km^2 between 1984 and 2015 at an annual declining rate of 3.231% (2.18km^2/year). The swamp coverage declined from 402.66km^2 to 287.60km^2, a declining rate of 3.22% (3.71km^2). The wetland of the system is rapidly depleting as found in the literature (Obiefuna *et al*., 2013) and is directly transformed into the built-up area; this was corroborated by the results of this research as wetlands are reducing around the Lagoon and built-up area is increasing towards the Lagoon coastline. The mangrove of the Lagos Lagoon is the third largest in the world (James *et al*., 2007). The results from the studies by Held *et al.,*(2003), James *et al*., (2007) and Taiwo & Areola (2009) supported the result from this research and affirm that the global, regional and local Nigeria wetlands are disappearing very fast from the coastal zone. The high rate of loss of the Lagoon wetlands have multifarious implications that could be extremely damaging to its inhabitants and residents because the various economic benefits (shoreline and storm protection, flood control, water quality, groundwater recharge and discharge, fisheries habitat, nursery for species habitat and recreation) of the coastal wetlands will be at high risk.

7.5.2 Relationship between urbanisation and depletion in the Lagoon ecosystem

The changes in the different land cover classifications in Chapter Four were discovered to be related to the urban growth around the Lagoon and the increase in population in Lagos State. The regression analysis between the wetland coverage available population data of Lagos State, especially the population of the local councils that surround the Lagoon shows two types of correlations (positive and negative). The positive correlation was the relationship that was exhibited between the built-up area and population growth, that is, as the population increases, urbanisation (built-up) increases as well. However, there is a negative correlation between the population growth and the remaining four land use classifications. The works of Ruiz-Luna & Berlanga-Robles (2003) and Sunday & Ajewole (2006) in comparison with the result of the study show that there is a correlation between the wetland depletion, urban growth and population around the Lagoon system, as built-up increases, the rest of the classified wetlands are reducing. Hence the rapid depletion in wetlands is attributed to a rapid increase in urbanisation which is as a result of an increase in the built-up area. This increase in urbanisation brings about a direct and rapid depletion in wetlands and there is a need to monitor the dynamics of LST in the ecosystem in order to mitigate against urban heat.

7.5.3 Characterisation of land covers types

Land use and land cover change (LUCC) is considered one of the principal forces that affect land and water degradation. The lack of consistent long-term land use and land cover change data is a critical gap in the knowledge of LUCC in monitoring ecosystem degradation and erosion in the northwestern region of the Lagoon. The Combination of Landsat reflective bands (1 -4) and a Landsat pseudo-true colour image (RGB) were applied to present spatially explicit land cover types in the Lagoon ecosystem. This combination enabled a clear identification of the features in the Lagoon wetland ecosystem. Nevertheless, it was not possible to determine the various land-cover types within the Lagoon ecosystem because of the quality of the resolution of the images used

(Landsat). To get a better land-cover type in any study site using a remote sensing method, an image of better spectral and spatial resolution is required (Andrew & Ustin, 2008; Yang *et al.,* 2003; Yu *et al.,* 2006), this has limited the separation of classification types because of lack of information. This limitation has the capability, for this study, to affect the estimation of the emissivity values of the land cover classifications types discussed in section 3.6.2.2 (Lo & Quattrochi, 2003; Weng, Lu & Schubring, 2004).

7.5.4 Land cover classification

The result of the land cover classification in Chapter Four, section 4.9, displays that the cluster analysis method (Parajka *et al.,* 2010) worked well to satisfy the land cover classification types. Yet, insufficiency of available information regarding the spectral and spatial resolutions of the datasets did not allow discriminating between and therefore classify different vegetation types, this was explained by Pettorelli *et al.,*(2005) and Kerr & Ostrovsky (2003) that it has been difficult at times to discern direct and indirect effects of environmental changes owing to limited information about vegetation at large temporal and spatial scales. Also, Yu *et al.,* (2006) supported this result, that while high-resolution images provide more information than coarse resolution imagery for detailed observation on vegetation, progressively smaller spatial resolution does not necessarily benefit classification accuracy and performance. Consequently, the number of wavebands used does not resolve differences in vegetation colour and brightness, and so the vegetation types cannot be classified separately. Therefore, abstraction or generalisation of small features in the study area is unavoidable since the spatial resolution of the Landsat image is limited to 30m resolution. In order to investigate more accurately, the use of a higher spectral and spatial resolution image must be inevitably considered (Yu *et al.*, 2006).

7.5.5 Relationship between NDVI and LST changes

The result of the investigation in this section shows that the generality of the NDVI-LST relationship of the climatic/radiation regime over the Lagoon ecosystem during the

December-January period when cloud cover is at the minimum. Results of the NDVI and LST show that the western region of the Lagoon ecosystem (with Somolu and Lagos Island LGA) exhibits the highest LST values and low NDVI values. At this region, there is almost no vegetation cover, and a consequential high rate of evapotranspiration that favours latent exchange between ground surface and atmosphere as compared with a built up area (Wilson *et al.,* 2003; Yue *et al.,* 2007). This is in agreement with Salvati *et al.* (2012), Salvati & Zitti (2012) and Pettorelli *et al*. (2005) who write that vegetation land cover is a basic sensitivity indicator for change or deterioration in the landscape. Interestingly, Kosmas *et al.* (2000) supported the result by acknowledging vegetation and land use classification as attributes of the landscape heavily affected by urbanisation. It was postulated that the different predominant urban expansion (compact and sprawl) existing at the western and extreme eastern parts of the lagoon ecosystem impact differently on the vegetation quality that exists in the regions homogenising landscapes and underscoring the contradiction in areas with high or low NDVI against LST (Salvati & Sabbi, 2011). The extreme eastern part of the study location (Ikorodu and Ibeju-Lekki) exhibit the highest NDVI values and low LST (Figure 4.40, Section 4.11) because of the predominant vegetation cover.

7.5.6 Spatio-temporal coastline changes

The several changes on the Lagoon ecosystem investigated in this study that includes an urban increase and depletion in the ecosystem wetlands are believed to be having a consequent effect on the coastline of the Lagoon which must have caused an increase or decrease in the area of the Lagoon at different locations on its coastline. The assessment of the spatial and temporal changes along the coastline was an outcome of the model developed in this research using ArcGIS ModelBuilder. The model was applied using five delineated Lagoon coastline map derived from Landsat image. The results show that reclamation between 1990 and 2016 came to 15,125,170m^2 (15.125) km^2; this implies that the Lagoon has reduced in surface area by this amount. On the other hand, the model computed landward retreat of 4,214,994m^2 (4.215km^2). This suggests a ratio of reclamation to recession to be approximately 4 to 1, and hence the Lagoon's surface area is reducing. The approximate surface area of the Lagoon as at 2010 was approximately 208km^2 (Balogun *et al.,* 2011). The reduction in the surface area has been confirmed by the modelling of the Lagoon as approximately 204.51km^2, inferring from the model result generated from 2016 coastline of the Lagoon. Hence the model has been found useful as an engine that can be used for coastline monitoring.

7.5.7 Dynamics of the Lagoon sea-bed

A lagoon system and its adjacent basins are dynamic on different spatial and temporal scales. As human activities increase with increased urbanisation, the volume of sediment accreting into the Lagoon is assumed to be increasing on daily basis. This, in turn, influences the natural morphology of the lagoon coastline. Van Der Wal & Pye (2003) investigated the morphological change in estuaries with the use of historical bathymetric charts. Again, Hicks & Hume (1997) determined sand volume and bathymetric changes on an ebb-tidal delta using repeated bathymetric surveys and they were able to detect net sand gains or losses over the ebb-tidal delta. The repeated bathymetric surveys were treated independently even though they were plotted together on the same ArcGIS interface. They exhibited that the accuracy of the surface-fitting and determinations of mean surface levels varied depending on the local seabed topography (Hicks & Hume, 1997), hence to avoid error and uncertainty, an interpolation method (kriging) that supported the local geographic spread of the data was adopted. A Triangular Irregular Network-(TIN) was chosen because it incorporates original height (Z) values not estimates; hence the calculation of volumes at different spatial locations and differences in mean bed levels between the repeated surveys was performed.

The result shows that over a six-year period that the repeated bathymetric data covered, the Lagoon decreased in depth by an average of 0.16m (0.026m/year). Without any dredging or other removal, the study area of the lagoon will have gained 1.3m of sediment in a 50 year period. Indeed, this result supports Kjerfve (1994) and Barnes (1980) who said lagoons are short lived in geological time. This fact assisted to understand the choice of data type (temporal scale data) that is fit to detect short-term changes in any lagoon as it was in the research case study area. Hence, a proper monitoring measure must be taken to avert the sudden disappearance of the Lagoon some decades hence.

The results in this section are also supported by Van Der Wal & Pye (2003) that indicated repeated and sequential bathymetric mapping or bed surveys can be used to calculate erosion rates and sedimentation. Sources of error and uncertainty are due mainly as a result of the surveying techniques used (Cracknell, 1999), the density of depth sampling points (Bowyer, 1992), interpolation and averaging (Burrough *et al.,* 2015) during compilation. The error and uncertainty due to survey methods and density of depth sampling are cared for during the survey exercise while the careful choice of the interpolation method helps to reduce the uncertainty that could result from interpolation. Documentation on the seabed morphological development of a lagoon is often needed to support its management, such as navigation, flood defence and habitat preservation, and the effects of changes in natural forcing factors (sea level rise) on the lagoon ecosystem. The present rate of change in the Lagoon sea floor must be made a baseline for assessing historic evolution in order to understand and predict its seabed dynamic trend. However, this demands both reliable data as well as consistent effective survey methods.

7.5.8 Salinity assessment of the Lagoon

An investigation into the salinity behaviour of the Lagoon was one of the major tests carried out by this study to assess the hydrodynamic characteristics of the system. Two seasonal (wet and dry) current meter data collections were made on the Lagoon where salinity data was measured, analysed and inferred. The result of average salinity on the system at four tidal scenarios during the two seasons indicated that at low water during the dry season the Lagoon salinity decreases from the outlet towards the inlet and in eastern region; this indicates that much of the sea water flow is into the Lagoon and drifts northward and eastward. However, in the wet season, a high inflow of freshwater and abundant rainfall impacts a wide reduction in the salinity gradient. Simply put, the wide salinity variation between the dry and the wet seasons confirmed that the Lagoon is a fresh water entity during the wet season and brackish during the dry season.

Furthermore, the r-square from the ANOVA test performed on the salinity observation related to high water and time of observation shows a value of 0.48% and 27.73% for wet and dry season respectively. Therefore, the salinity variation during the wet season over a large spatial range of location might not be noticed, hence the salinity of the system is uniform to a large extent. In contrast, variability in observations related to high water seems to depend on time, and thus salinity varies spatially with time and tidal band. Additionally, an analysis of salinity and temperature tells where there is possible well-mixed water mass. The study of Xu *et al.* (2008) confirms the possibility of the change of water mass at the intersection of salinity and temperature in T-S diagram analysis.

7.5.9 Result of mixing/stratification process in the Lagoon

Many researchers have applied mixing/stratification to estuaries (Dyer, 1991), when Richardson number, one of the major indicator for testing mixing/stratification of water body, is converted to potential energy it found its wide use in investigation of mixing pattern of lakes and lagoon (Gale *et al.*, 2006) and frequently in coastal seas (Rippeth & Simpson, 1996). A conceptual framework (Figure 3.9, Section 3.12) for gathering the data that will compute the Richardson number was designed by the author; this was used to compute the Richardson number for the field research data during the dry and wet seasons. Using the theoretical Richardson numbers scale suggested by Dyer (1991) and

Venayagamoorthy & Koseff (2016) that at a low Richardson number ($R_i < 0.25$), turbulent kinetic energy mixing occurs and at a high Richardson number, energy decays and the water column is stable. The result from this section of the study shows that during the dry season the Lagoon is more stable than in the wet season because a small portion of the computed Richardson number (about 5%) in the dry season was less than zero while 33% was less than zero in the wet season. However, the wet season result exhibits significant vertical mixing which implies that there is sufficient turbulence to overcome density layering. The percentage ratio of the Lagoon stratification during the dry season to that of the wet season was computed to be approximately 1:7.

In the course of computing flushing time for the Lagoon, the flux rate through all the channels that empty into the Lagoon and amount of fresh water concentration were calculated (Table 7.1), it was found that flux rate was almost double at the outlet and the main inlet and the fresh water concentration higher in wet season. This, of course, influences the result of the computed flushing time for the two seasons.

Table 7.1: Computed flux at the entrance distributed in flow channels that empty into the Lagoon and flushing time during dry and wet season

Computed flux channels that enter into the Lagoon		
	Dry Season	Wet Season
Location	Flux rate (m^3/s)	Flux Rate (m^3/s)
Ogun River	197.18	135.87
Majidun River	282.84	418.86
Outlet	1608.71	2942.50
Ebute Meta Channel	88.32	181.93
Ogudu	31.88	45.65
Computed fractional fresh water concentration and Flushing time		
Season	Freshwater concentration	Flushing time (day)
Dry	0.606	26.07
Wet	0.700	21.99

The result indicated the flushing time of approximately 26 days and 22 days for dry and wet season respectively. It is evident from the computed flushing time that most of the potential pollutant or industrial effluent from the industrial area surrounding the Lagoon may be flushed from the Lagoon in the time estimated as a flushing time of the Lagoon during the dry and wet season. However, high pollutant levels can remain in pockets of stagnant water much longer in an area such as Ogudu region where the local fishermen build artificial barriers to create stagnant water for fishing purposes.

7.6 Model development

In addition to the model built with the help ArcGIS 10.1 in section 7.3, a novel idea was employed on the model of Morris *et al.,* (2002) on the response of coastal wetlands to rising sea level by introducing dimensional homogeneity with their original equation. The assumptions made were that the exponential proportionality m =1 and n vary and the long-term sea level is rising at a linear rate over time. The results from this model show that sediment accretion was increasing at the same rate when the exponential proportionality was equal but the rate of sediment accretion at a certain marsh depth (1.3m) started changing with a distinct impact of the exponential factor at a higher exponential proportion the rate of sediment accretion was lower than when the exponential factor was small. Furthermore, the effect that the relative sea level rise could have on the Lagoon ecosystem either in wet or dry season building on Morris *et al.,*(2002) was modelled assuming the rate of sea level rises at a different rate per year (0.02m, 0.025m, 0.03m, 0.035m, 0.04m and 0.08m). The outcome decreases in the rate of sediment deposition as a time of year increases, and after about 18 years a constant rate of change is maintained. Although, a significant difference was not noticed between the different rates of sea level rise, when the sea level suddenly changed to 0.08m the deposition rate jumped to almost double.

7.7 Investigation of lagoons spatio particle characterization

Two empirical methods were employed in this section. The first, an Andreasen pipette experiment for investigating the sediment characteristics of the Lagoon, and secondly a Hindered settling experiment used to assess the settling velocity of the Lagoon sediment. The results of the two experiments were derived from different spatial locations on the study site. The Andreasen results show that two locations on the Lagoon are assumed to be having unbalanced forces act on their settling capability, and hence points of inflexion were noticed on the graph that depicts the relationship between particle cumulative percent and particle diameter. Three scenarios were deduced from the results at seven locations, in accordance with Manning *et al.* (2010), macro-sediments encompassing result region of approximately cumulative of 85% - 98% (scenario 1 in Chapter 6 Section6.9.1) can be interpreted as fast settling macro-sediment constituting high rate of settling velocity compare to particles in scenarios 2 and 3 (Chapter 6 Section 6.9.1) where PSD cumulative percent was as low as 45% - 55%. Furthermore, the Hindered experiment shows that the Ogudu region recorded the lowest settling velocity. With the use of the Wentworth universal grain size chart, it was confirmed that the particles in the region are classified under very fine silt (mud). This was confirmed on site during data collection by visual observation of the state of the sediment that was accumulated in the region. Lastly, according to Stokes' Law, the settling particles in the Lagoon (with the assumption that they are spherical in shape) have a varying settling velocity that is uniquely related to the diameter of the particles at various spatial locations.

7.8 Further research

Doctoral research is a continuous phenomenon rather than discrete, therefore this study area is not limited in scope and time. The study has identified some research areas that will add more understanding to the morphological and hydrodynamic changes of global coastal lagoons. Such prospective areas of future study are identified thus:

7.8.1 Hypsography, hydro-hypsography and hydrological analysis

The spatial characteristics of the void space in any lagoon basins are important parameters that control the potential flooding of part of the drainage prism and the subsequent development of coastal lagoons. The computation of hydro-hypsometry on the Lagoon can be used to relate the fraction of water surface area at a specific elevation to the fraction of the Lagoon basin height. The hydro-hypsographic curve will explain the incremental change in the submerged land-surface area at different elevations. Since the environmental quality of any lagoon is strongly dependent on the water exchange over different parts of the system, variations in depth could be linked to the complex hypsographic characteristics of previous surfaces and sediment accumulation on such areas. Any future study will help to identify very shallow areas that provide optimal sites for wetland colonisation and intermediate depths that are good site for colonisation by submerged aquatic vegetation but are often subject to turbulence caused by currents and waves

7.8.2 The use of NDVI to study a coastal lagoon ecosystem in order to differentiate between natural variation and variation arising from human activities

Unlike field-based measurements of ecosystem function, which cannot easily be converted to estimates of function across an entire ecosystem of a lagoon, remote sensing can provide simultaneous estimates of ecosystem function over wide areas. Remote sensing of vegetation (NDVI) offers promising and urgently needed measurements of ecosystem function at spatial scales that are most comparable to the extents of human influence on the environment. Combining high-resolution satellite image and field-based habitat data, landscape structure and habitat species abundance information can be derived. NDVI measurements, especially when joined with information on land use in any lagoon ecosystem, can be used to study variation in the existence of native grasslands and the cultivated fields. Land use emerged in this case as a most important influence on the ecosystem function as could be measured by yearly or every two years integrated

NDVI. Such study will help to measure the rate at which human activities increases along the coastal Lagoon.

7.8.3 Lagoon modelling for coastal management

With the advent of new technological developments of numerical models along with computational systems, hydrodynamic modelling is becoming part of the field of computational fluid dynamics. The common basis of the modelling activities is to transform conservation principles into quantification tools. Therefore, many researchers have found hydrodynamic models useful in modelling the dynamics of the coastal lagoons and estuaries especially in the developed countries; no precise structured hydrodynamic model, to the best of author’s knowledge, has been applied either for management or monitoring of changes on the Lagoon. Applications of these models to different coastal areas, lagoons and estuaries have shown an ability to simulate complex features of changes. In geospatial applications, all hydrodynamic models vary in both time and space, and the output results of any hydrodynamic model in any geospatial coastal lagoon can include water level monitoring, trends in vertical velocities, salinity and temperature variations, stratification patterns, and flow pattern. These can be shown visually for the end users and could help in the management the Lagoon.

7.8.4 Gravity variation and lagoon stratification

Spatial gravity variation for different points on the Lagoon can be computed using the parameters: density and two constant variables (radius of the earth and gravitational constant). With the use of the Valeport current meter, it is possible to measure the density anomaly which could be converted to density. It could be used in the computation of spatial gravity variation at the different point where measurement is taken. This computation could be compared with the derived gravitation variation from the data from any latest gravity field satellite (for example Gravity Recovery And Climate Experiment Follow-on (GRACE Follow-on)) and see if they are exactly the same. If not a conversion programme could be developed to transform the derived gravity to measured gravity and vice versa. In the absence of equipment for data collection, the developed algorithm for conversion could be used for transformation of data from CHAMP to measured data and hence the results could be used to monitor the effects it could impact on the system stratification.

7.8.5 Sea-level rise and its impact on the coastal lagoon

Numerous possible responses to sea level rise abound among which are inundation and flooding (Church & White, 2006; Church & White, 2011; Nicholls & Cazenave, 2010; Nicholls *et al.,* 2011; Nicholls *et al.,* 2007). Prospective studies that focus on identifying the complex nature of the changes along the Nigeria coast should precede assessment of sea level; hence the two combined can be evaluated to see the effect of sea level rise on the Lagoon and other lagoons bounded along the Nigerian coastline. This is because the same rate of sea level rise scenario could bring different degrees of impact on different spatial locations on the coastline.

7.8.6 Population growth, industrial expansion and anthropogenic activities, and their impact on coastal lagoon and its ecosystem

It will be of good benefit to constantly estimate the quantity of ecosystem loss due to urbanisation, industrial expansion and anthropogenic activities going on simultaneously along the Lagoon. Assessing the social impacts and health implications due to ecosystem depletion on the various habitats around the Lagoon could assist in decision making and proffering a management framework for maintenance of the Lagoon and its ecosystem. Integration of the various ecosystem demographic data into a GIS model will be highly useful in the conduct and long-term sustainability of this kind of future research.

7.9 Summary

Chapter seven is the general discussion section of the research findings. It considered the limitation that is attached with the research relative to the study area, general problems that were encountered in the course of carrying out the study, and programming and analysis tools. Furthermore, the research findings as compared to the literature were able to reinforce what has already been found by other authors that a lagoon has not a long (geological) life span, hence it gradually goes into extinction. Also, because this type of research has never been done in the Lagos Lagoon, there were new findings relative to the Lagoon which were discussed in detail.

The fact that the research topic is new to the study area, opens up privileges for further research, and a few of such studies that can be carried out in the Lagoon are discussed under this section.

7.10 Conclusion

This Chapter has been able to sum up the findings in this research that Lagos Lagoon is highly vulnerable to morphodynamic changes, and these changes include, as investigated in this research, the coastline of the Lagoon, interaction and the adjustment of its floor topography, and likewise fluid hydrodynamics processes and sequences of change involving the Lagoon spatial sediment. Hence, it has been discovered from the research finding that the Lagoon faces the challenge of sustainability and extinction due to poor planning across its ecosystem.

CHAPTER EIGHT
CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

Mitigating the potential effects of morphological and hydrodynamic changes on a lagoon is a controversial issue, with many unanswered questions and a great portion of uncertainty. This Chapter reviews the aim and objectives in terms of the findings, it draws conclusions on the extent of the morphological changes on the Lagos Lagoon ecosystem and its bottom configuration, the dynamic nature of its water, the inferences drawn from the results, and the model (synthesis) that was developed to predict morphological and hydrodynamic changes in the system. The Chapter proceeds to highlight the contribution of the study to the body of knowledge in marine and coastal researches and finally it makes recommendations concerning the inferences of the research.

8.2 Conclusions

The general conclusion highlights the achievements of the study and shows that the following:

- Remote sensing methodology to investigate the changes around and along the coastal Lagoon, have shown great possibilities in this approach. The results of land cover changes in mapping the Lagoon ecosystem address questions regarding the possibility of satellite data to detect impacts of morphological changes around and along the coastline of any coastal lagoon.
- NDVI results revealed that the values around the most developed urban area in the Lagoon ecosystem are closer to zero, while values around regions of less or no development are higher and tend toward one (1). Also, the results of LST play a vital role in ascertaining the results of the NDVI. The LST result indicates the

value of surface temperature as a function of the amount of vegetation (present or lost). Any location with low vegetation (low NDVI) shows high LST values and vice versa. Therefore it can be concluded that satellite data such as Landsat TM, ETM+ and Landsat 8 data has the capability of detecting temporal changes on lagoon ecosystems and along its coastline.

- The use of a functional mechanism to build a model for detecting the coastline changes of the Lagoon was made possible with the application of ArcGIS 10.1. The model derived has been useful to ascertain the degree of transgression and regression of the lagoon coastline. From literature, it was discovered in 2010 that the Lagoon surface area was 208 $km^{2.}$ However, the results of the model revealed the present surface area to be approximately 204 km^2. Hence, the Lagoon is gradually disappearing. Likewise, the Lagoon seafloor, specifically in the region used as a case study, the depths have decreased by an average of 0.16m (0.026 m/year). By implication, without any dredging, the study area will have gained 1.3m of sediment in 50 years period (Section 5.6).
- The use of the (gradient) Richardson number was explored as an indicator of the lagoon mixing during the period studied. When the lagoon presents a high degree of stratification the Richardson number increases and turbulence and mixing are reduced. When the lagoon is less stratified the vertical shear becomes more important breaking the stability of the salinity structure and favouring mixing due to entrainment and turbulent diffusion. The variation in the Richardson number shows that mixing occurs mainly during the wet season, while more stable conditions tend to occur where stratification is dominant and that was the experience of the system in the dry season.
- The finding from the assessment of spatial-temporal salinity variations of the Lagoon shows that the system is brackish during the dry season and fresh during

the wet season. The results of temperature and salinity analysis (T-S) show that the Lagoon exhibits constant changes of water mass during the dry season which is not the situation during the wet season. The implication is that during the wet season there is a small velocity shear in the Lagoon, and hence there is stability and no mixing - the opposite of the dry season.

- An inference from the computed flushing time (using freshwater fraction method) of the Lagoon shows that most of the potential pollutant or effluent from the industrial locations around the Lagoon coupled with saline water will take 26 days and 22 days to be flushed during the dry and wet seasons respectively, from the Lagoon.
- The use of simple models (derived and functional mechanisms) was considered for different reasons (representation of idea, prediction, understanding a process, and communication of idea); the models developed in this research, though, designed for local prediction, it can be applied to any global lagoon as long as the input parameters for the models are available in such a location.
- Lastly, the two empirical methods explored in particle distribution and settling velocity, revealed the Lagoon spatio-particle characterisation during the period studied. From one of the findings, the western region where the main and largest industrial channels empty waste into the Lagoon is gradually being filled with micro-sediment and also the settling velocity is very low, an indication that the region of the Lagoon water is filled with suspended particles, and hence flushed away after a while.

8.3 Contributions to knowledge

As it has been established from the literature and in the list of references, there is variability in the global lagoon context, their ecosystems and the drivers that cause changes in them. Although some of the factors that cause changes in the system are the same (such as climate change, air temperature, seasonal precipitation, salinity, tide, and fresh water inflow) there are other factors that are dominant in certain lagoons (such as degree of human impacts and shoreline hardening) due to their geographical location. The main contributions of this research are presented as follows:

- Research on the morphology or hydrodynamics of the coastal lagoon is sparse in Nigeria; in fact, this research approach has not been conducted on the Lagos Lagoon in time or spatial magnitude. Hence the stages of methods for the processing of Landsat data, GIS analysis and characterisation of spatial NDVI and LST analysis used in this study will be of help for future users studying land cover variability on coastal lagoon ecosystem and land cover type generally.
- A GIS model was implemented together with a functional approach under seasonal conditions (wet and dry season); this produces both qualitative and quantitative results for the salt intrusion, stratification and water profile status. This methodology will be useful for coastal managers and waterway users to simulate and monitor immediate prevailing tidal scenarios and in the future to produce stratification scenario maps for areas of interest.
- Furthermore, the model for coastline changes developed in this study with the help of GIS aids the workflow, and documents all the processes undertaken. This model will be useful for users to simulate future coastline changes along any coastal lagoon to produce maps for the phenomena of interest.
- The research provides an up-to-date comprehensive review of the current state of the Lagos Lagoon (localised and generalised for lagoons in tropical Africa) with special attention to morphological and hydrodynamic changes.

- The novel idea employed by the Morris et al (2002) model of the response of coastal wetlands to rising sea levels by introducing dimensional homogeneity with their original equation is a contribution to the knowledge in this area of research.
- Lastly, this research investigated the changes in the Lagoon ecosystem over a period of 31 years, and thus the spatial and temporal variability in vegetation health and temperature that might be related to the Lagoon ecosystem has been identified. The results will provide guidance that can potentially inform the Nigerian Government on the management of the Lagoon, and effects the present changes in the system could be having on the long term livelihood of people and the quality of the environment.

8.4 Recommendations

With the level of morphological and hydrodynamic changes discovered within and around the Lagos Lagoon through findings from this research, recommendations are proposed with the view to set up a sustainable management stakeholder committee by the Nigerian government to ensure sustainable actions are taken towards the maintenance of the Lagoon system. Hence the following recommendations are suggested:

- The major limiting factor in this research is the lack of both scientific and historic hydrodynamic and morphological data. Advances in coastal lagoon data and information which promote detection, attribution and prediction of global and large scale regional changes are current goals for the Global Observing System (GOS) of the United Nations. However, the coastal region of Nigeria is lagging behind in up to date data and information of this sentinel ecosystem for coastal observations of global change. Hence there is an urgent demand to set up a regional coastal observatory station in Nigeria so as to continuously collect coastal data and information for the purpose of holistic monitoring and management of the regional coastal zone. Such data should also be made available for academic research purposes.

- With the economic and social importance of Lagoon to the growth and well-being of the inhabitants, which includes implementation of maritime and coastal activities and forecasting, there should be adequate funding for research of this magnitude.
- For constant and detailed hydrodynamic analysis of the Lagoon, the government, through some of the universities or research centres along the coastal region, should set up institutions that will embark on adopting world-class numerical hydrodynamic modelling, and train various researchers on the use of these models. Such steps will advance the growth of coastal research generally in Nigeria and put the coast in a better position to be monitored, managed and sustained.
- Regular staff development training for researchers in coastal processes and policy implementation in Nigeria is deemed necessary for the sustainable management of lagoons and surrounding coastal environments.
- Data management and archiving should be held in high esteem for rapidly changing marine environments such as lagoons, as it will help in more timely and proper dissemination of data to researchers and the general public who may need it at any time. Major obstacles in data management include data control, data availability, and integrity of the dataset, documentation and metadata and method of updating. Thus, the Nigerian government should ensure a dedicated coastal observatory body, for example the Lagos Coastal Observatory (LCO), is established for the management of the Lagos Lagoon coast. The duties of such an organisation should include: methods of data collection, the integrity of the data collected, the derivation of coastal information datasets, regional coastal monitoring and running a data management centre. These measures will ensure

the users take good advantage of marine and coastal data from the centre and proficiently use such data.

- For better management and sustainability of the Lagoon, consistent measurement should go on henceforth especially measurement regarding bathymetry survey, flow and mixing in the Lagoon.

References

Abere, S. & Ekeke, B. (2011) 'The Nigerian mangrove and wildlife development'. *Mediterranean Journal of Social Sciences*, pp 107.

Achudume, A. (2007) 'Assessment of farmland sediments after flooding in Ubeji Land in Niger Delta of Nigeria'. *Environmental Monitoring and Assessment*, 135 (1-3). pp 335-338.

Adejuwon, J. O. (2012) 'Rainfall seasonality in the Niger Delta Belt, Nigeria'. *Journal of Geography and Regional Planning*, 5 (2). pp 51.

Adelekan, I. O. (2010) 'Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria'. *Environment and Urbanization*, 22 (2). pp 433-450.

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R. & Rockström, J. (2005) 'Social-ecological resilience to coastal disasters'. *Science*, 309 (5737), pp. 1036-1039.

Adlam, K. (2014) 'Coastal lagoons: Geologic evolution in two phases'. *Marine Geology*,

Afinowi, M. (1975) 'The biology of Anadara senilis and Gryphaea (Crassostrea) gasar in West African waters', *FAO, Rome (Italy). Fisheries Dept. FAO/CIFA Symposium on Aquaculture in Africa. Accra (Ghana). 30 Sep 1975.*

Ajagbe, F., Osibona, A. & Otitoloju, A. (2012) 'Diversity of the edible fishes of the Lagos Lagoon, Nigeria and the public health concerns based on their Lead (Pb) content'. *International Journal of Fisheries and Aquaculture*, 4 (3). pp 55-62.

Ajao, E. & Fagade, S. (1990a) 'A study of the sediments and communities in Lagos Lagoon, Nigeria'. *Oil and Chemical Pollution*, 7 (2). pp 85-117.

Ajao, E. & Fagade, S. (1990b) 'Production and population dynamics of Pachymelania aurita Müller'. *Archiv für Hydrobiologie*, 120 (1). pp 97-109.

Ajao, E. A. (1996) *Review of the state of pollution of the Lagos Lagoon.* NIOMR technical paper. s.l.: s.n.

Akoni, O. (2014). Rainy season: Lagos moves to avert flooding. *Vanguard*, [online] p.44. Available at: http://www.vanguardngr.com [Accessed 10 March 2016].

Alcala, A. (1998) 'Community-based coastal resource management in the Philippines: a case study'. *Ocean & Coastal Management*, 38 (2). pp 179-186.

Alexandrakis, G., Karditsa, A., Poulos, S., Ghionis, G., Kampanis, N. & Sydow, A. (2010) 'An assessment of the vulnerability to erosion of the coastal zone due to a potential rise of sea level: the case of the Hellenic Aegean coast'. *Environmental Systems,[Ed. Achim Sydow], in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK*, Alkan, R., Kalkan, Y. & Aykut, N. (2006) 'Sound velocity determination with empirical formulas and bar check', *Proceedings of 23rd FIG Congress, Munich*.

Allaby, M. (2008) 'Oxford Dictionary of Earth Sciences. ed. Allaby, M., Third edn. Oxford: Oxford University Press.

Allen, D. W. (2011) *Getting to know ArcGIS - ModelBuilder.* First edn. USA: ESRI Press.

Alongi, D.M. (1998). Coastal ecosystem processes. CRC Marine Science Series, 3. CRC Press: Boca Raton.

Alves, F., Roebeling, P., Pinto, P. & Batista, P. (2009) 'Valuing ecosystem service losses from coastal erosion using a benefits transfer approach: a case study for the Central Portuguese coast'. *J Coastal Res*, 56 pp 1169-1173.

Amaeze, N. H., Egonmwan, R. I., Jolaosho, A. & Otitoloju, A. (2012) 'Coastal environmental pollution and fish species diversity in Lagos Lagoon, Nigeria'. *International Journal of Environmental Protection*, 2 (11). pp 8-16.

Amaeze, N. H., Schnell, S., Sozeri, O., Otitoloju, A. A., Egonmwan, R. I., Arlt, V. M. & Bury, N. R. (2015) 'Cytotoxic and genotoxic responses of the RTgill-W1 fish cells in combination with the yeast oestrogen screen to determine the sediment quality of Lagos lagoon, Nigeria'. *Mutagenesis*, 30 (1). pp 117-127.

Amos, C., Bergamasco, A., Umgiesser, G., Cappucci, S., Cloutier, D., DeNat, L., Flindt, M., Bonardi, M. & Cristante, S. (2004) 'The stability of tidal flats in Venice Lagoon—the results of in-situ measurements using two benthic, annular flumes'. *Journal of Marine Systems*, 51 (1). pp 211-241.

Amos, C., Villatoro, M., Helsby, R., Thompson, C., Zaggia, L., Umgiesser, G., Venturini, V., Are, D., Sutherland, T. & Mazzoldi, A. (2010) 'The measurement of sand transport in two inlets of Venice lagoon, Italy'. *Estuarine, Coastal and Shelf Science*, 87 (2). pp 225-236.

Andrew, M. E. & Ustin, S. L. (2008) 'The role of environmental context in mapping invasive plants with hyperspectral image data'. *Remote Sensing of Environment*, 112 (12).pp 4301-4317.

Anthony, A., J. Atwood, P. August, C. Byron, S. Cobb, C. Foster, C. Fry, A. Gold, K. Hagos, L. Heffner, D. Q. Kellogg, K. Lellis-Dibble, J. J. Opaluch, C. Oviatt, A. Pfeiffer-Herbert, N. Rohr, L. Smith, T. Smythe, J. Swift, and N. Vinhateiro. 2009. Coastal lagoons and climate change: ecological and social ramifications in U.S. Atlantic and Gulf coast ecosystems. *Ecology and Society* 14(1): 8. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art8/

Araújo, I., Dias, J. & Pugh, D. (2008) 'Model simulations of tidal changes in a coastal lagoon, the Ria de Aveiro (Portugal)'. *Continental Shelf Research*, 28 (8). pp 1010-1025.

Ashton, A. D., Donnelly, J. P. & Evans, R. L. (2008) 'A discussion of the potential impacts of climate change on the shorelines of the Northeastern USA'. *Mitigation and Adaptation Strategies for Global Change*, 13 (7). pp 719-743.

Artioli, Y., Bendoricchio, G. & Palmeri, L. (2005) 'Defining and modelling the coastal zone affected by the Po river (Italy)'. *Ecological Modelling*, 184 (1). pp 55-68.

Atkinson, M. & Smith, S. (1983) 'C: N: P ratios of benthic marine plants'. *Limnology and Oceanography*, 28 (3). pp 568-574.

Ayoola, S. & Kuton, M. (2009) 'Seasonal variation in fish abundance and physico-chemical parameters of Lagos lagoon, Nigeria'. *African Journal of Environmental Science and Technology*, 3 (5). pp 149-156.

Balaguer, P., Sardá, R., Ruiz, M., Diedrich, A., Vizoso, G. & Tintore, J. (2008) 'A proposal for boundary delimitation for integrated coastal zone management initiatives'. *Ocean & Coastal Management*, 51 (12). pp 806-814.

Balogun, K., Ladigbolu, I. & Ariyo, A. (2011) 'Ecological assessment of a coastal shallow lagoon in Lagos, Nigeria: A bio-indicator approach'. *Journal of Applied Sciences and Environmental management*, 15 (1).

Barnes, R. (1989) 'The coastal lagoons of Britain: an overview and conservation appraisal'. *Biological Conservation*, 49 (4). pp 295-313.

Barnes, R. S. K. (1974) *Estuarine biology.* Edward Arnold London.

Barnes, R. S. K. (1980) *Coastal lagoons.* vol. 1. Cambridge University Press.

Barsi, J. A., Schott, J. R., Palluconi, F. D. & Hook, S. J. (2005) 'Validation of a web-based atmospheric correction tool for single thermal band instruments', *Optics & Photonics 2005*. International Society for Optics and Photonics, pp. 58820E-58820E-58827.

Bass, S., Aldridge, J., McCave, I. & Vincent, C. (2002) 'Phase relationships between fine sediment suspensions and tidal currents in coastal seas'. *Journal of Geophysical Research: Oceans*, 107 (C10).

Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S. N., Helder, D., Helmer, E., Nemani, R., Oreopoulos, L. & Schott, J. (2008) 'Free access to Landsat imagery'. *Science*, 320 pp 1011-1011.

Bentum, K.M. van. 2012. The Lagos coast - Investigation of the long-term morphological impact of the Eko Atlantic City project, *MSc Thesis*, Delft University of Technology.

Bhattacharya, J. P. & Giosan, L. (2003) 'Wave-influenced deltas: Geomorphological implications for facies reconstruction'. *Sedimentology*, 50 (1). pp 187-210.

Biggs, R. B. & Cronin, L. E. (1981) 'Special characteristics of estuaries'. *Estuaries and nutrients.* Springer, pp 3-23.

Bird, E. C. (1994) 'Physical setting and geomorphology of coastal lagoons'. *Elsevier Oceanography Series*, 60 pp 9-39.

Bird, E. C. F. (2008) *Coastal Geomophology - An Introduction.* Second Edition edn. West Sussex, England: John Wiley & Sons Ltd. Second Edition

Blauw, A. N., Los, H. F., Bokhorst, M. & Erftemeijer, P. L. (2009) 'GEM: a generic ecological model for estuaries and coastal waters'. *Hydrobiologia*, 618 (1). pp 175-198.

Board, M. (1987) Responding to Changes in Sea Level:: Engineering Implications. National Academies Press.

Boesch, D. F. (2002) 'Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems'. *Estuaries*, 25 (4). pp 886-900.

Bowen, J. L. & Valiela, I. (2001) 'The ecological effects of urbanization of coastal watersheds: historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries'. *Canadian Journal of Fisheries and Aquatic Sciences*, 58 (8). pp 1489-1500.

Bowyer, J. (1992) 'Basin changes in Jervis Bay, New South Wales: 1894–1988'. *Marine Geology*, 105 (1).pp 211-224.

Brannen, J. (2005) 'Mixing methods: The entry of qualitative and quantitative approaches into the research process'. *International Journal of Social Research Methodology*, 8 (3). pp 173-184.

Brehmer, P., Do Chi, T., Laugier, T., Galgani, F., Laloë, F., Darnaude, A. M., Fiandrino, A. & Mouillot, D. (2011) 'Field investigations and multi-indicators for shallow water lagoon management: perspective for societal benefit'. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 21 (7). pp 728-742.

Brenes, C. L., Hernández, A. & Ballestero, D. (2007) 'Flushing time in Perlas Lagoon and Bluefields Bay, Nicaragua'. *Investigaciones Marinas*, 35 pp 1.

Bricker S. B & Ferreira J. G (2008) 'ASSETS eutrophication assessment: method and application'. *Land-Oceans Interactions in the Coastal Zone* (LOICZ), 9 pp. [www.loicz.org/imperia/md/content/loicz/science/assets_eutropphication_assessment.pdf].

Brito, A. C., Newton, A., Fernandes, T. F. & Tett, P. (2011) 'The role of microphytobenthos on shallow coastal lagoons: a modelling approach'. *Biogeochemistry*, 106 (2). pp 207-228.

Brito, A. C., Newton, A., Tett, P. & Fernandes, T. F. (2012) 'How will shallow coastal lagoons respond to climate change? A modelling investigation'. *Estuarine, Coastal and Shelf Science*, 112 pp 98-104.

Brummer, C. J., Abbe, T. B., Sampson, J. R. & Montgomery, D. R. (2006) 'Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA'. *Geomorphology,* 80 (3). pp 295-309.

Bruneau, N., Fortunato, A. B., Dodet, G., Freire, P., Oliveira, A. & Bertin, X. (2011) 'Future evolution of a tidal inlet due to changes in wave climate, sea level and lagoon morphology (Óbidos Lagoon, Portugal)'. *Continental Shelf Research*, 31 (18). pp 1915-1930.

Bryman, A. (2006) 'Integrating quantitative and qualitative research: how is it done?'. *Qualitative Research*, 6 (1). pp 97-113.

Burrough, P. A., McDonnell, R. A., McDonnell, R. & Lloyd, C. D. (2015) *Principles of geographical information systems.* Oxford University Press.

Cameron, R. (2011) 'Mixed methods research: The five Ps framework'. *The Electronic Journal of Business Research Methods*, 9 (2). pp 96-108.

Carniello, L., Defina, A., Fagherazzi, S. & D'alpaos, L. (2005) 'A combined wind wave–tidal model for the Venice lagoon, Italy'. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 110 (F4).

Carrasco, A., Ferreira, Ó. & Roelvink, D. (2016) 'Coastal lagoons and rising sea level: A review'. *Earth-Science Reviews*, 154 pp 356-368.

Carter, R. W. G. & Woodroffe, C. D. (1994) *Coastal evolution: Late Quaternary Shoreline Morphodynamics.* Cambridge University Press.

Carter, R. W. G. (1995) Coastal Environments - An Introduction to the Physical, Ecological and Cultural Systems of Coastlines ed. Printing, F., Fifth edn. London, U.K.: Academic Press Limited.

Cayocca, F. (2001) 'Long-term morphological modeling of a tidal inlet: the Arcachon Basin, France'. *Coastal Engineering*, 42 (2). pp 115-142.

Chanda, B. & Majumder, D. D. (2009) *Digital Image Processing and Analysis.* 12 edn. New Delhi - 110001: PHI Learning Private Limited.

Chander, G., Markham, B. L. & Helder, D. L. (2009) 'Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors'. *Remote Sensing of Environment*, 113 (5). pp 893-903.

Chang, C. L. & Lee, R. C. T. (2014) *Symbolic Logic and Mechanical Theorem Proving.* Academic Press, Inc. London.

Change, C. (2001) 'The scientific basis, intergovernmental panel on climate change'. *by JT Houghton, Y. Ding, DJ Griggs, et al*,

Change, I. P. O. C. (2007) 'Climate change 2007: The physical science basis'. *Agenda*, 6 (07). pp 333.

Chavez, P. S. (1996) 'Image-based atmospheric corrections-revisited and improved'. *Photogrammetric Engineering and Remote Sensing*, 62 (9). pp 1025-1035.

Chen, F., Ye, H. & Zhao, X. (2012) Making Use of the Landsat 7 SLC-OFF ETM+ Image Through Different Recovering Approaches. INTECH Open Access Publisher.

Church, J. A. & White, N. J. (2006) 'A 20th century acceleration in global sea-level rise'. *Geophysical research letters*, 33 (1).

Church, J. A. & White, N. J. (2011) 'Sea-level rise from the late 19th to the early 21st century'. *Surveys in Geophysics*, 32 (4-5). pp 585-602.

Clark, J. R. (2009) *Coastal seas: the conservation challenge.* John Wiley & Sons.

Cleveland, C. C. & Liptzin, D. (2007) 'C: N: P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass?'. *Biogeochemistry*, 85 (3). pp 235-252.

Conde, D., Aubriot, L. & Sommaruga, R. (2000) 'Changes in UV penetration associated with marine intrusions and freshwater discharge in a shallow coastal lagoon of the Southern Atlantic Ocean'. *Marine Ecology Progress Series*, 207 (1). pp 19-31.

Connolly, N., Buchanan, C., O’Connell, M., Cronin, N., O’Mahony, C., Sealy, H., Kay, D., Buckley, S., 2001. Assessment of Human Activity in the Coastal Zone: A Research Project Linking Ireland and Wales. Marine Institute, Dublin, Ireland.

Contanza, R., d’Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R. & Paruelo, J. (1997) 'The value of the world’s ecosystem services and natural capitals'. *Nature*, 387 (6630). pp 253-260.

Cracknell, A. (1999) 'Remote sensing techniques in estuaries and coastal zones: an update'. *International Journal of Remote Sensing*, 20 (3).pp 485-496.

Creel, L. (2003) *Ripple effects: population and coastal regions.* Population Reference Bureau Washington, DC.

Creswell, J. W. & Clark, V. L. P. (2007) *Designing and conducting mixed methods research.* Wiley Online Library.

Creswell, J. W. (2013) *Research design: Qualitative, quantitative, and mixed methods approaches.* Sage Publications.

Crooks, S. & Turner, R. (1999) 'Integrated coastal management: sustaining estuarine natural resources'. *Advances in Ecological Research*, 29 pp 241-289.

Cummins, V., Mahony, O., Connolly, N., 2004. In: Coastal and Marine Resources Centre, (Ed.). Review of Integrated Coastal Zone Management & Principals of Best Practice. *Environmental Research Institute*, University College, Cork, Ireland.

da Silva, J. F. & Duck, R. W. (2001) 'Historical changes of bottom topography and tidal amplitude in the Ria de Aveiro, Portugal trends for future evolution'. *Climate Research*, 18 (1-2). pp 17-24.

Dahl, T. E. (2005) 'Status and trends of wetlands in the conterminous United States 1998 to 2004'.

Daramola, A. & Ibem, E. O. (2010) 'Urban environmental problems in Nigeria: Implications for sustainable development'. *Journal of Sustainable Development in Africa*, 12 (1). pp 124-145.

Davies, J. & Moses, C. A. (1964) *A morphogenic approach to world shorelines.*

Davis, R. A. & Hayes, M. O. (1984) 'What is a wave-dominated coast?'. *Marine Geology*, 60 (1). pp 313-329.

de Noronha Vaz, E., Nijkamp, P., Painho, M. & Caetano, M. (2012) 'A multi-scenario forecast of urban change: A study on urban growth in the Algarve'. *Landscape and Urban Planning*, 104 (2). pp 201-211.

Desvouges, W. H., Naughton, M. C. & Parsons, G. R. (1992) 'Benefits transfer: conceptual problems in estimating water quality benefits using existing studies'. *Water Resources Research*, Vol. 28, No. 3 (1992): pp. 675-683.

De Swart, H. & Zimmerman, J. (2009) 'Morphodynamics of tidal inlet systems'. *Annual Review of Fluid Mechanics*, 41 pp 203-229.

Debenay, J.-P., Eichler, B. B., Duleba, W., Bonetti, C. & Eichler-Coelho, P. (1998) 'Water stratification in coastal lagoons: its influence on foraminiferal assemblages in two Brazilian lagoons'. *Marine Micropaleontology*, 35 (1). pp 67-89.

Denscombe, M. (2008) 'Communities of practice a research paradigm for the mixed methods approach'. *Journal of Mixed Methods Research*, 2 (3). pp 270-283.

Denzin, N. K. & Lincoln, Y. S. (2009) 'Qualitative research'. *Yogyakarta: PustakaPelajar*,

Dias JM, Valentim JM, Sousa MC (2013) A Numerical Study of Local Variations in Tidal Regime of Tagus Estuary, Portugal. PLoS ONE 8(12): e80450. doi:10.1371/journal.pone.0080450

Dias, J., Lopes, J. & Dekeyser, I. (2000) 'Tidal propagation in Ria de Aveiro lagoon, Portugal'. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25 (4). pp 369-374.

Dias, J., Sousa, M., Bertin, X., Fortunato, A. & Oliveira, A. (2009) 'Numerical modeling of the impact of the Ancão Inlet relocation (Ria Formosa, Portugal)'. *Environmental Modelling & Software*, 24 (6). pp 711-725.

Dinis, J., Henriques, V., Freitas, M., Andrade, C. & Costa, P. (2006) 'Natural to anthropogenic forcing in the Holocene evolution of three coastal lagoons (Caldas da Rainha valley, western Portugal)'. *Quaternary International*, 150 (1). pp 41-51.

Donelan, M. A., Drennan, W. M. & Katsaros, K. B. (1997) 'The air-sea momentum flux in conditions of wind sea and swell'. *Journal of Physical Oceanography*, 27 (10). pp 2087-2099.

Don-Pedro, K., Oyewo, E. & Otitoloju, A. (2004) 'Trend of heavy metal concentrations in Lagos lagoon ecosystem, Nigeria'. *West African Journal of Applied Ecology*, 5 (1).

Douillet, P., Ouillon, S. & Cordier, E. (2001) 'A numerical model for fine suspended sediment transport in the southwest lagoon of New Caledonia'. *Coral Reefs*, 20 (4). pp 361-372.

Dronkers, J. (1988) 'Inshore/offshore water exchange in shallow coastal systems'. *Coastal-offshore ecosystem interactions.* Springer, pp 3-39.

Duck, R. W. & da Silva, J. F. (2012) 'Coastal lagoons and their evolution: A hydro-morphological perspective'. *Estuarine, Coastal and Shelf Science*, 110 pp 2-14.

Dumas, P., Kulbicki, M., Chifflet, S., Fichez, R. & Ferraris, J. (2007) 'Environmental factors influencing urchin spatial distributions on disturbed coral reefs (New Caledonia, South Pacific)'. *Journal of Experimental Marine Biology and Ecology*, 344 (1). pp 88-100.

Dupra, V., Smith, S., Marshall Crossland, J. & Crossland, C. (2000) 'Estuarine systems of the South China Sea region: carbon, nitrogen and phosphorus fluxes'. *LOICZ Reports and Studies*, 14 pp 156pp.

Dutta, V. (2012) 'Land use dynamics and Peri-urban growth characteristics reflections on master plan and urban suitability from a sprawling North Indian city'. *Environment and Urbanization Asia*, 3 (2). pp 277-301.

Dyer, K. & Manning, A. (1999) 'Observation of the size, settling velocity and effective density of flocs, and their fractal dimensions'. *Journal of Sea Research*, 41 (1). pp 87-95.

Dyer, K. (1991) 'Circulation and mixing in stratified estuaries'. *Marine Chemistry*, 32 (2-4). pp 111-120.

Dyer, K. (1996) 'The definition of the Severn estuary', *Proceedings of the Bristol Naturalists' Society*. pp. 53-66.

Dyer, K. (1997) *Estuaries: A physical introduction.* 2nd ed. John Wiley & Sons Publisher: London.

Dyer, K. R. (1973) *Estuaries: a physical introduction.* John Wiley & Sons: London.

e Silva, J. D. L., Lopes, C. L., Picado, A., Sousa, M. C. & Dias, J. M. (2014) 'Tidal dispersion and flushing times in a multiple inlet lagoon'. *Journal of Coastal Research*, (70). pp 598.

Edokpayi, C. & Ayorinde, A. (2005) 'Physical, chemical and macrobenthic invertebrate fauna characteristics of swampy water bodies within University of Lagos, Nigeria'. *West African Journal of Applied Ecology*, 8 (1).

Elliott, M. & McLusky, D. S. (2002) 'The need for definitions in understanding estuaries'. *Estuarine, Coastal and Shelf Science*, 55 (6). pp 815-827.

Emmanuel, B. & Onyema, I. (2007) 'The plankton and fishes of a tropical creek in south-western Nigeria'. *Turk. J. Fish. Aquat. Sci*, 7 (2). pp 105-113.

Etuonovbe, A. K. (2011) 'The devastating effect of flooding in Nigeria', *FIG working week*. pp. 2011.

Fernandes, E. H. L., Dyer, K. R. & Moller, O. O. (2005) 'Spatial gradients in the flow of southern Patos Lagoon'. *Journal of Coastal Research*, pp 759-769.

Ferrarin, C., Umgiesser, G., Roland, A., Bajo, M., De Pascalis, F., Ghezzo, M. & Scroccaro, I. (2016) 'Sediment dynamics and budget in a microtidal lagoon—A numerical investigation'. *Marine Geology*, 381 pp 163-174.

Fischer, H. B. (1976) 'Mixing and dispersion in estuaries'. *Annual Review of Fluid Mechanics*, 8 (1). pp 107-133.

Fischer, H. B., List, J. E., Koh, C. R., Imberger, J. & Brooks, N. H. (2013) *Mixing in inland and coastal waters.* Elsevier.

Flemer, D. A., Mackiernan, G. B., Nehlsen, W., Tippie, V. K., Biggs, R. B., Blaylock, D., Burger, N. H., Davidson, L. C., Haberman, D. & Price, K. S. (1983) 'Chesapeake Bay: A profile of environmental change'. *US Environmental Protection Agency, Washington, DC*, 199

Forbes, D., Orford, J., Carter, R., Shaw, J. & Jennings, S. (1995) 'Morphodynamic evolution, self-organisation, and instability of coarse-clastic barriers on paraglacial coasts'. *Marine Geology*, 126 (1). pp 63-85.

Folke, C. (2006) 'Resilience: The emergence of a perspective for social–ecological systems analyses'. *Global Environmental Change*, 16 (3), pp. 253-267.

Friedman, G. M. & Sanders, J. E. (1978) *Principles of sedimentology.* Wiley.

Friedrichs, C. T. & Aubrey, D. G. (1988) 'Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis'. *Estuarine, Coastal and Shelf Science*, 27 (5). pp 521-545.

Gale, E., Pattiaratchi, C. & Ranasinghe, R. (2006) 'Vertical Mixing Processes in Intermittently Closed and Open Lakes and Lagoons, and the dissolved oxygen response'. *Estuarine, Coastal and Shelf Science*, 69 (1). pp 205-216.

Gale, E., Pattiaratchi, C. & Ranasinghe, R. (2006) 'Vertical mixing processes in Intermittently Closed and Open Lakes and Lagoons, and the dissolved oxygen response'. *Estuarine, Coastal and Shelf Science*, 69 (1).pp 205-216.

Galperin, B., Sukoriansky, S. & Anderson, P. S. (2007) 'On the critical Richardson number in stably stratified turbulence'. *Atmospheric Science Letters*, 8 (3). pp 65-69.

Garcia, A., Vieira, J. & Winemiller, K. (2001) 'Dynamics of the shallow-water fish assemblage of the Patos Lagoon estuary (Brazil) during cold and warm ENSO episodes'. *Journal of Fish Biology*, 59 (5). pp 1218-1238.

Garvine, R. W. (1985) 'A simple model of estuarine subtidal fluctuations forced by local and remote wind stress'. *J. Geophys. Res*, 90 (11). pp 945-911.

Gastwirth, J. L., Gel, Y. R. & Miao, W. (2009) 'The impact of Levene's test of equality of variances on statistical theory and practice'. *Statistical Science*, pp 343-360.

Gesch, D. B. (2009) 'Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise'. *Journal of Coastal Research*, pp 49-58.

Glaister, R. & Nelson, H. (1974) 'Grain-size distributions, an aid in facies identification'. *Bulletin of Canadian Petroleum Geology*, 22 (3). pp 203-240.

Gonenc, I. E. & Wolflin, J. P. (2004) Coastal lagoons: ecosystem processes and modelling for sustainable use and development. CRC Press.

Google Corporation, (2006). "Google Earth - a 3D interface to the planet". [Online]. Available: http://www.earth.google.com/ (Accessed 15th April 2014).

Gordon, A. (1990) 'Coastal lagoon entrance dynamics'. *Coastal Engineering Proceedings*, 1 (22).

Gordon, D. C., Boudreau, P., Mann, K., Ong, J., Silvert, W., Smith, S., Wattayakorn, G., Wulff, F. & Yanagi, T. (1996) *LOICZ biogeochemical modelling guidelines.* vol. 5. LOICZ Core Project, Netherlands Institute for Sea Research.

Gorman, L., Morang, A. & Larson, R. (1998) 'Monitoring the coastal environment; part IV: mapping, shoreline changes, and bathymetric analysis'. *Journal of Coastal Research*, pp 61-92.

Gornitz, V. (1990) 'Vulnerability of the East Coast, USA to future sea level rise'. *Journal of Coastal Research*, 9 pp 201-237.

Gouveia, G., Trindade, G., Nery, L. E. M. & Muelbert, J. H. (2015) 'UVA and UVB Penetration in the Water Column of a South West Atlantic Warm Temperate Estuary and its Effects on Cells and Fish Larvae'. *Estuaries and Coasts*, 38 (4). pp 1147-1162.

Grachev, A. A., Andreas, E. L., Fairall, C. W., Guest, P. S. & Persson, P. O. G. (2013) 'The critical Richardson number and limits of applicability of local similarity theory in the stable boundary layer'. *Boundary-Layer Meteorology*, 147 (1). pp 51-82.

Granja, H., Rocha, F., Matias, M., Moura, R., Caldas, F., Marques, J. & Tareco, H. (2010) 'Lagoa da Apúlia: A residual lagoon from the Late Holocene (NW coastal zone of Portugal)'. *Quaternary International*, 221 (1). pp 46-57.

Greenwood, B. (1969) 'Sediment parameters and environment discrimination: an application of multivariate statistics'. *Canadian Journal of Earth Sciences*, 6 (6). pp 1347-1358.

Grimm, N. B., Grove, J. G., Pickett, S. T. & Redman, C. L. (2000) 'Integrated Approaches to Long-Term Studies of Urban Ecological Systems Urban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory'. *BioScience*, 50 (7). pp 571-584.

Guha, A. & Kumar, K. V. (2014) 'Potential of thermal emissivity for mapping of greenstone rocks and associated granitoids of Hutti Maski Schist belt, Karnataka'. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40 (8). pp 423.

Gutman, G., Byrnes, R. A., Masek, J., Covington, S., Justice, C., Franks, S. & Headley, R. (2008) 'Towards monitoring land-cover and land-use changes at a global scale: the global land survey 2005'. *Photogrammetric engineering and remote sensing*, 74 (1). pp 6-10.

Guyondet, T. & Koutitonsky, V. G. (2008) 'Tidal and residual circulations in coupled restricted and leaky lagoons'. *Estuarine, Coastal and Shelf Science*, 77 (3). pp 396-408.

Halpern, B. S., Longo, C., Hardy, D., McLeod, K. L., Samhouri, J. F., Katona, S. K., Kleisner, K., Lester, S. E., O'Leary, J. & Ranelletti, M. (2012) 'An index to assess the health and benefits of the global ocean'. *Nature*, 488 (7413). pp 615-620.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C. & Fox, H. E. (2008) 'A global map of human impact on marine ecosystems'. *Science*, 319 (5865). pp 948-952.

Hansen, D. V. & Rattray, M. (1966) 'New Dimensions in Estuary Classification'. *Limnology and Oceanography*, 11 (3). pp 319-326.

Harley, C. D., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J., Thornber, C. S., Rodriguez, L. F., Tomanek, L. & Williams, S. L. (2006) 'The impacts of climate change in coastal marine systems'. *Ecology letters*, 9 (2). pp 228-241.

Harris, G., 'Lagoons'. In: Jørgensen, Sven Erik., Fath B.D. (Eds) (2008) *Encyclopedia of Ecology.* Academic Press, Oxford.

Hart, D. (2007) 'River-mouth lagoon dynamics on mixed sand and gravel barrier coasts'. *Journal of Coastal Research*, 50 pp 927-931.

Hartmann, D. & Christiansen, C. (1992) 'The hyperbolic shape triangle as a tool for discriminating populations of sediment samples of closely connected origin'. *Sedimentology*, 39 (4). pp 697-708.

Haslett, S. K. (2009) *Coastal Systems.* ed. Mannion, R.G.A.M., Routledge Introductions to Environmental Series. Second edition. London: Routledge

Held, A., Ticehurst, C., Lymburner, L. & Williams, N. (2003) 'High-resolution mapping of tropical mangrove ecosystems using hyperspectral and radar remote sensing'. *International Journal of Remote Sensing*, 24 (13).pp 2739-2759.

Helmuth, B., Harley, C. D., Halpin, P. M., O'Donnell, M., Hofmann, G. E. & Blanchette, C. A. (2002) 'Climate change and latitudinal patterns of intertidal thermal stress'. *Science*, 298 (5595).pp 1015-1017.

Hicks, D. M. & Hume, T. M. (1997) 'Determining sand volumes and bathymetric change on an ebb-tidal delta'. *Journal of Coastal Research*, pp 407-416.

Hilldale, R. C. & Raff, D. (2008) 'Assessing the ability of airborne LiDAR to map river bathymetry'. *Earth Surface Processes and Landforms*, 33 (5).pp 773.

Hinrichsen, D. (1997) Coastal waters of the world: trends, threats, and strategies. Island Press.

Howarth, R., Anderson, D., Cloern, J., Elfring, C., Hopkinson, C., Lapointe, B., Malone, T., Marcus, N., McGlathery, K. & Sharpley, A. (2000) 'Nutrient pollution of coastal rivers, bays, and seas'. *Issues in Ecology*, 7 (7). pp 1-14.

Hristov, T., Miller, S. & Friehe, C. (2003) 'Dynamical coupling of wind and ocean waves through wave-induced air flow'. *Nature*, 422 (6927). pp 55-58.

Iovanna, R. & Griffiths, C. (2006) 'Clean water, ecological benefits, and benefits transfer: a work in progress at the US EPA'. *Ecological economics*, 60 (2), pp. 473-482.

Isebor, C. E. (2004) 'Marine biodiversity in Nigeria–the known and the unknown. National report'.

James, G. K., Adegoke, J. O., Saba, E., Nwilo, P. & Akinyede, J. (2007) 'Satellite-based assessment of the extent and changes in the mangrove ecosystem of the Niger Delta'. *Marine Geodesy*, 30 (3).pp 249-267.

Jay, D. A., Geyer, W. R. & Montgomery, D. R. (2000) 'An ecological perspective on estuarine classification'. *Estuarine science: a synthetic approach to research and practice. Island Press, Washington DC*, pp 149-176.

Jimenez, J. A. & Sanchez-Arcilla, A. (1997) 'Physical impacts of climatic change on deltaic coastal systems (II): driving terms'. *Climatic Change*, 35 (1). pp 95-118.

Johnson, R. B., Onwuegbuzie, A. J. & Turner, L. A. (2007) 'Toward a definition of mixed methods research'. *Journal of Mixed Methods Research*, 1 (2). pp 112-133.

Johnston, C. M. & Gilliland, P. M. (2000) 'Investigating and managing water quality in saline lagoons'

Junior, L. C. C., Brandini, N., Knoppers, B. A., Mizerkowski, B. D., Sterza, J. M., Ovalle, A. R. C. & Medeiros, P. R. P. (2013) 'Assessment of the trophic status of four coastal lagoons and one estuarine delta, eastern Brazil'. *Environmental Monitoring and Assessment*, 185 (4). pp 3297-3311.

Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., Gutman, G. G., Panov, N. & Goldberg, A. (2010) 'Use of NDVI and land surface temperature for drought assessment: Merits and limitations'. *Journal of Climate*, 23 (3). pp 618-633.

Karydis, M., University of the Aegean, University of the Aegean, L. I. D. o. E. S. & Lekkas, T. (2009) 'Eutrophication assessment of coastal waters based on indicators: a literature review', *Proceedings of the International Conference on Environmental Science and Technology*. University of the Aegean, Chania(Greece).

Kaufman, Y. J., Karnieli, A. & Tanré, D. (2000) 'Detection of dust over deserts using satellite data in the solar wavelengths'. *Geoscience and Remote Sensing, IEEE Transactions on*, 38 (1). pp 525-531.

Kelaher, B., Underwood, A. & Chapman, M. (2003) 'Experimental transplantations of coralline algal turf to demonstrate causes of differences in macrofauna at different tidal heights'. *Journal of Experimental Marine Biology and Ecology*, 282 (1).pp 23-41.

Kennish, M. J. & Paerl, H. W. (2010) Coastal lagoons: critical habitats of environmental change. CRC Press.

Kenov, I. A., Garcia, A. C. & Neves, R. (2012) 'Residence time of water in the Mondego estuary (Portugal)'. *Estuarine, Coastal and Shelf Science*, 106 pp 13-22.

Kerr, J. T. & Ostrovsky, M. (2003) 'From space to species: ecological applications for remote sensing'. *Trends in Ecology & Evolution*, 18 (6).pp 299-305.

Kirk, R. (1991) 'River-beach interaction on mixed sand and gravel coasts: a geomorphic model for water resource planning'. *Applied Geography*, 11 (4). pp 267-287.

Kjerfve, B. & Knoppers, B. A. (1991) *Tidal choking in a coastal lagoon.* Wiley and Sons.

Kjerfve, B. & Magill, K. E. (1989) 'Geographic and hydrodynamic characteristics of shallow coastal lagoons'. *Marine Geology*, 88 (3).pp 187-199.

Kjerfve, B. (1986) 'Comparative oceanography of coastal lagoons'. *Estuarine Variability*, pp 63-81.

Kjerfve, B. (1994a) *Coastal lagoon processes.* Access Online via Elsevier, (Accessed in May 2014).

Kjerfve, B. (1994b) 'Coastal lagoons'. *Elsevier Oceanography Series*, 60 pp 1-8.

Klemas, V. (2010) 'Remote sensing techniques for studying coastal ecosystems: an overview'. *Journal of Coastal Research*, 27 (1). pp 2-17.

Klemas, V. (2013) 'Remote sensing of emergent and submerged wetlands: an overview'. *International Journal of Remote Sensing*, 34 (18). pp 6286-6320.

Knoppers, B. (1994) 'Aquatic primary production in coastal lagoons'. *Elsevier Oceanography Series*, 60 pp 243-286.

Kosmas, C., Gerontidis, S. & Marathianou, M. (2000) 'The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece)'. *Catena*, 40 (1).pp 51-68.

Kuenzer, C., van Beijma, S., Gessner, U. & Dech, S. (2014) 'Land surface dynamics and environmental challenges of the Niger Delta, Africa: Remote sensing-based analyses spanning three decades (1986–2013)'. *Applied Geography*, 53 pp 354-368.

Kuleli, T., Guneroglu, A., Karsli, F. & Dihkan, M. (2011) 'Automatic detection of shoreline change on coastal Ramsar wetlands of Turkey'. *Ocean Engineering*, 38 (10). pp 1141-1149.

Kummu, M., De Moel, H., Ward, P. J. & Varis, O. (2011) 'How close do we live to water? A global analysis of population distance to freshwater bodies'. *PLoS One*, 6 (6). pp e20578.

Kuwahara, S. (1938) 'The velocity of sound in sea water and calculation of the velocity for use in sonic sounding'. *Japanese Journal of Astronomy and Geophysics*, 16 pp 1.

Lario, J., Spencer, C., Plater, A., Zazo, C., Goy, J. & Dabrio, C. J. (2002) 'Particle size characterisation of Holocene back-barrier sequences from North Atlantic coasts (SW Spain and SE England)'. *Geomorphology*, 42 (1). pp 25-42.

Lasserre, P. & Campostrini, P. (2007) Lagoons and Coastal Wetlands in the Global Change Context: Impact and Management Issues: Selected papers of the International Conference" CoastWetChange", Venice 26-28 April 2004. vol. 192. Springer Science & Business Media.

Li, C. & O'Donnell, J. (1997) 'Tidally driven residual circulation in shallow estuaries with lateral depth variation'. *Journal of Geophysical Research: Oceans (1978–2012)*, 102 (C13). pp 27915-27929.

Liang, S., Fang, H. & Chen, M. (2001) 'Atmospheric correction of Landsat ETM+ land surface imagery. I. Methods'. *Geoscience and Remote Sensing, IEEE Transactions on*, 39 (11). pp 2490-2498.

Lloret, J., Marín, A. & Marín-Guirao, L. (2008) 'Is coastal lagoon eutrophication likely to be aggravated by global climate change?'. *Estuarine, Coastal and Shelf Science*, 78 (2). pp 403-412.

Lo, C. & Quattrochi, D. A. (2003) 'Land-use and land-cover change, urban heat island phenomena, and health implications'. *Photogrammetric Engineering & Remote Sensing*, 69 (9).pp 1053-1063.

Long, A. J., Plater, A. J., Waller, M. P. & Innes, J. B. (1996) 'Holocene coastal sedimentation in the Eastern English Channel: new data from the Romney Marsh region, United Kingdom'. *Marine Geology*, 136 (1). pp 97-120.

Lopes, J. F., Dias, J. M. & Dekeyser, I. (2006) 'Numerical modelling of cohesive sediments transport in the Ria de Aveiro lagoon, Portugal'. *Journal of Hydrology*, 319 (1). pp 176-198.

Lopes, C. L., Plecha, S., Silva, P. A. & Dias, J. M. (2013) 'Influence of morphological changes in a lagoon flooding extension: case study of Ria de Aveiro (Portugal)'. *Journal of Coastal Research*, 65 (sp2). pp 1158-1163.

Lotze, H. K., Lenihan, H. S., Bourque, B. J., Bradbury, R. H., Cooke, R. G., Kay, M. C., Kidwell, S. M., Kirby, M. X., Peterson, C. H. & Jackson, J. B. (2006) 'Depletion, degradation, and recovery potential of estuaries and coastal seas'. *Science*, 312 (5781). pp 1806-1809.

Lu, D., Li, G., Moran, E., Batistella, M. & Freitas, C. C. (2011) 'Mapping impervious surfaces with the integrated use of Landsat Thematic Mapper and radar data: A case study in an urban–rural landscape in the Brazilian Amazon'. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66 (6). pp 798-808.

Lu, D., Mausel, P., Brondizio, E. & Moran, E. (2004) 'Change detection techniques'. *International Journal of Remote Sensing*, 25 (12). pp 2365-2401.

Lumborg, U. & Pejrup, M. (2005) 'Modelling of cohesive sediment transport in a tidal lagoon—an annual budget'. *Marine Geology*, 218 (1). pp 1-16.

Malinen, M. I., Mariescu-Istodor, R. & Fränti, P. (2014) 'K-means: Clustering by gradual data transformation'. *Pattern Recognition*, 47 (10). pp 3376-3386.

Manning, A. J. & Bass, S. J. (2006) 'Variability in cohesive sediment settling fluxes: Observations under different estuarine tidal conditions'. *Marine Geology*, 235 (1). pp 177-192.

Manning, A., Schoellhamer, D., Mehta, A., Nover, D. & Schladow, S. (2010) 'Video measurements of flocculated sediment in lakes and estuaries in the USA', *Proceedings of the Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, Riviera Hotel, Las Vegas, Nevada, USA, 27th June–1st July 2010*.

Manning, A. J. and Dyer, K.R. (2007). Mass settling flux of fine sediments in Northern European estuaries: measurements and predictions. Marine Geology, 245, 107-122, doi:10.1016/j.margeo.2007.07.005.

Manning, A.J., Whitehouse, R.J.S. and Uncles, R.J. (in press). Flocculation Measurements. In: R.J. Uncles and S. Mitchell (Eds), ECSA practical handbooks on survey and analysis methods: Estuarine and coastal hydrography and sedimentology, Cambridge University Press.

Marinov, D., Norro, A. & Zaldívar, J.-M. (2006) 'Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore)'. *Ecological Modelling*, 193 (1). pp 52-68.

Martins, F. & Fernandes, E. (2004) 'Hydrodynamic model intercomparison for the Patos Lagoon (Brazil)'. *Proceedings of EMS*, pp 123-126.

Masek, J. G., Huang, C., Wolfe, R., Cohen, W., Hall, F., Kutler, J. & Nelson, P. (2008) 'North American forest disturbance mapped from a decadal Landsat record'. *Remote Sensing of Environment*, 112 (6). pp 2914-2926.

McGlathery, K. J., Sundback, K. & Anderson, I. C. (2007) 'Eutrophication in shallow coastal bays and lagoons: the role of plants in the coastal filter'. *Marine Ecology Progress Series*, 348 (1). pp 1-18.

McGranahan, G., Balk, D. & Anderson, B. (2007) 'The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones'. *Environment and Urbanization*, 19 (1). pp 17-37.

McGranahan, G., Marcotullio, P., Bai, X., Balk, D., Braga, T., Douglas, I., Elmqvist, T., Rees, W., Satterthwaite, D. & Songsore, J. (2005) 'Urban systems'. *Ecosystems and Human Well-Being, Current State and Trends, Findings of the Condition and Trends Working Group. Millennium Ecosystem Assessment Series*, 1

McInnes, K., Walsh, K., Hubbert, G. & Beer, T. (2003) 'Impact of sea-level rise and storm surges on a coastal community'. *Natural Hazards*, 30 (2). pp 187-207.

McLusky, D. & Elliott, M. (2007) 'Transitional waters: a new approach, semantics or just muddying the waters?'. *Estuarine, Coastal and Shelf Science*, 71 (3). pp 359-363.

Michel, D. & Howa, H. (1997) 'Morphodynamic behaviour of a tidal inlet system in a mixed-energy environment'. *Physics and Chemistry of the Earth*, 22 (3). pp 339-343.

Mikhailov, V., Gorin, N., Gorin, S., Gorin, L., Mikhailov, V. & Gorin, S. (2012) 'New definitions, regionalization, and typification of river mouth areas and estuaries as their parts'. *Water Resources*, 39 (3). pp 247-260.

Mitsch, W. J. & Gosselink, J. G. (2000) 'The value of wetlands: the importance of scale and landscape setting'. *Ecological Economics*, 35 (1). pp 25-33.

Mohanty, P. & Panda, B. (2009) 'Circulation and mixing processes in Chilika lagoon'. *Indian Journal of Marine Sciences*, 38 (2). pp 205.

Möller, O. O., Castaing, P., Fernandes, E. H. L. & Lazure, P. (2007) 'Tidal frequency dynamics of a southern Brazil coastal lagoon: choking and short period forced oscillations'. *Estuaries and Coasts*, 30 (2). pp 311-320.

Moller, O. O., Stech, J. & Math, M. M. (1996) 'The Patos Lagoon summertime circulation and dynamics'. *Continental Shelf Research*, 16 (3). pp 335-351.

Monbet, Y. (1992) 'Control of phytoplankton biomass in estuaries: a comparative analysis of microtidal and macrotidal estuaries'. *Estuaries*, 15 (4). pp 563-571.

Monsen, N. E., Cloern, J. E., Lucas, L. V. & Monismith, S. G. (2002) 'A comment on the use of flushing time, residence time, and age as transport time scales'. *Limnology and Oceanography*, 47 (5). pp 1545-1553.

Montaño-Ley, Y., Peraza-Vizcarra, R. & Páez-Osuna, F. (2007) 'The tidal hydrodynamics modeling of the Topolobampo coastal lagoon system and the implications for pollutant dispersion'. *Environmental Pollution*, 147 (1). pp 282-290.

Morris, J. T., Sundareshwar, P., Nietch, C. T., Kjerfve, B. & Cahoon, D. R. (2002) 'Responses of coastal wetlands to rising sea level'. *Ecology*, 83 (10). pp 2869-2877.

Mouillot, D., Gaillard, S., Aliaume, C., Verlaque, M., Belsher, T., Troussellier, M. & Do Chi, T. (2005) 'Ability of taxonomic diversity indices to discriminate coastal lagoon environments based on macrophyte communities'. *Ecological Indicators*, 5 (1). pp 1-17.

Nairn, R.B.; MacIntosh, K.J.; Hayes, M.O.; Nai, G.; Anthonio, S.L., and Valley, W.S., 1998. Coastal erosion at Keta Lagoon, Ghana – Large Scale Solution to a Large Scale Problem. In: Proceedings of the 1998: 26th International Conference on Coastal Engineering, ICCE- 98 (Copenhagen, Denmark), pp. 3192–3205.

Nanson, G. C. & Hickin, E. J. (1986) 'A statistical analysis of bank erosion and channel migration in western Canada'. *Geological Society of America Bulletin,* 97 (4). pp 497-504.

NASA. (2011). National Aeronautics and Space Administration. "The Landsat program". [Online]. Available: http://www.landsat.gsfc.nasa.gov/about/landsat1.html; http://www.landsathandbook.gsfc.nasa.gov/excel_docs/d.exlsTable [Accessed 12th November 2015].

National Population Commission of Nigeria, 2006 (http://www.population.gov.ng/).

Neves, F. (2010) 'Dynamics and hydrology of the Tagus estuary: results from in situ observations', PhD thesis, University of Lisbon Portugal, available at: http://repositorio.ul.pt/handle/10451/2003 (Accessed: April 2015).

Newton, A. & Mudge, S. M. (2003) 'Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal'. *Estuarine, Coastal and Shelf Science*, 57 (1). pp 73-85.

Newton, A., Icely, J., Falcao, M., Nobre, A., Nunes, J., Ferreira, J. & Vale, C. (2003) 'Evaluation of eutrophication in the Ria Formosa coastal lagoon, Portugal'. *Continental Shelf Research*, 23 (17). pp 1945-1961.

Nichols, M. & Allen, G. (1981) 'Sedimentary processes in coastal lagoons'. *UNESCO Technical Papers in Marine Science (UNESCO),*

Nichols, M. M. & Boon, J. D. (1994) 'Sediment transport processes in coastal lagoons'. *Elsevier Oceanography Series*, 60 pp 157-219.

Nicholls, R. & Hoozemans, F. (1996) 'The Mediterranean: vulnerability to coastal implications of climate change'. *Ocean & Coastal Management*, 31 (2). pp 105-132.

Nicholls, R. J. & Cazenave, A. (2010) 'Sea-level rise and its impact on coastal zones'. *Science*, 328 (5985). pp 1517-1520.

Nicholls, R. J., Hoozemans, F. M. & Marchand, M. (1999) 'Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses'. *Global Environmental Change*, 9 pp S69-S87.

Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., De Gusmao, D., Hinkel, J. & Tol, R. S. (2011) 'Sea-level rise and its possible impacts given a 'beyond 4 C world'in the twenty-first century'. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 369 (1934). pp 161-181.

Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., De Gusmao, D., Hinkel, J. & Tol, R. S. (2011) 'Sea-level rise and its possible impacts given a ‘beyond 4 C world’in the twenty-first century'. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 369 (1934).pp 161-181.

Nicholls, R. J., Wong, P. P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S., Woodroffe, C. D., Abuodha, P. & Arblaster, J. (2007) 'Coastal systems and low-lying areas'.

Nixon, S., Ammerman, J., Atkinson, L., Berounsky, V., Billen, G., Boicourt, W., Boynton, W., Church, T., Ditoro, D. & Elmgren, R. (1996) 'The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean'. *Nitrogen cycling in the North Atlantic Ocean and its Watersheds.* Springer, pp 141-180.

Nixon, S. W. & Buckley, B. A. (2002) '“A strikingly rich zone”—nutrient enrichment and secondary production in coastal marine ecosystems'. *Estuaries*, 25 (4). pp 782-796.

Nkwoji, J., Igbo, J., Adeleye, A., Obienu, J. & Tony-Obiagwu, M. (2010a) 'Implications of bioindicators in ecological health: a study of a coastal lagoon, Lagos, Nigeria'.

Nkwoji, J., Igbo, J., Mojekwu, T., Obienu, J. & Adeleye, A. (2012) 'Hydrochemistry and Sediment Characteristics of Western Lagos Lagoon, Nigeria'. *Continental Journal of Environmental Sciences*, 5 (2).

Nkwoji, J., Onyema, I. & Igbo, J. (2010) 'Wet season spatial occurrence of phytoplankton and zooplankton in Lagos Lagoon, Nigeria'. *Science World Journal*, 5 (2).

Nkwoji, J., Yakub, A., Ajani, G., Balogun, K., Renner, K., Igbo, J., Ariyo, A. & Bello, B. (2010) 'Seasonal variations in the water chemistry and benthic macroinvertebrates of a south western Lagoon, Lagos, Nigeria'. *Journal of American Science*, 6 (3). pp 85-92.

Obiefuna, J. N., Nwilo, P. C., Atagbaza, A. O. & Okolie, C. J. (2012) 'Land cover dynamics associated with the spatial changes in the wetlands of Lagos/Lekki Lagoon system of Lagos, Nigeria'. *Journal of Coastal Research*, 29 (3). pp 671-679.

Obiefuna, J. N., Nwilo, P., Atagbaza, A. & Okolie, C. (2013) 'Spatial changes in the wetlands of Lagos/Lekki Lagoons of Lagos, Nigeria'. *Journal of Sustainable Development*, 6 (7).pp 123.

O'Brien, M.P., (1976). Note on tidal inlets on sandy shores. GITI report 5, prepared for US Army Coastal Engineering Research Centre by the University of California, Berkeley, USA.

Oertel, G. & Woo, H. (1994) 'Landscape classification and terminology for marsh in deficit coastal lagoons'. *Journal of Coastal Research*, pp 919-932.

Oey, L.-Y. (1984) 'On steady salinity distribution and circulation in partially mixed and well mixed estuaries'. *Journal of Physical Oceanography*, 14 (3). pp 629-645.

Ojeh, V. N., Balogun, A. & Okhimamhe, A. (2016) 'Urban-Rural Temperature Differences in Lagos'. *Climate*, 4 (2). pp 29.

Olapoju, O. A. & Edokpayi, C. A. (2014) 'Ecological study on the impact of mariculture fish cage site on the physico-chemical characteristics of Lagos Lagoon, South Western Nigeria'. *Journal of Ecology and The Natural Environment*, 6 (12). pp 398-405.

Olatunji, A. & Abimbola, A. (2010) 'Geochemical evaluation of the Lagos Lagoon sediments and water'. *World Applied Sciences Journal*, 9 (2). pp 178-193.

Oliveira, A., Fortunato, A. B. & Rego, J. R. (2006) 'Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos lagoon (Portugal)'. *Continental Shelf Research*, 26 (8). pp 917-942.

Olowu, R., Ayejuyo, O., Adewuyi, G., Adejoro, I., Denloye, A., Babatunde, A. & Ogundajo, A. (2010) 'Determination of heavy metals in fish tissues, water and sediment from Epe and Badagry Lagoons, Lagos, Nigeria'. *Journal of Chemistry*, 7 (1). pp 215-221.

Olsen, S. B. (2003) 'Frameworks and indicators for assessing progress in integrated coastal management initiatives'. *Ocean & coastal management*, 46 (3). pp 347-361.

Orford, J. D., Forbes, D. L. & Jennings, S. C. (2002) 'Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems'. *Geomorphology*, 48 (1). pp 51-85.

Oyebade, B., Emerhi, E. & Ekeke, B. (2010) 'Quantitative review and distribution status of mangrove forest species in West Africa'. *African Research Review*, 4 (2).

Oyedele, K. & Momoh, E. (2009) 'Evaluation of Sea-water intrusion in freshwater aquifers in a Lagoon Coast: a case study of the University of Lagos Lagoon, Akoka, Nigeria'. *New York Science Journal*, 2 (3). pp 1554-0200.

Pages, J. & Citeau, J. (1990) 'Rainfall and salinity of a Sahelian estuary between 1927 and 1987'. *Journal of Hydrology*, 113 (1). pp 325-341.

Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Dumitrescu, A., Gaume, E. & Hlavčová, K. (2010) 'Seasonal characteristics of flood regimes across the Alpine–Carpathian range'. *Journal of Hydrology*, 394 (1).pp 78-89.

Parece, T. E. & Campbell, J. B. (2013) 'Comparing urban impervious surface identification using Landsat and high resolution aerial photography'. *Remote Sensing*, 5 (10). pp 4942-4960.

Pari, Y., Murthy, R., Subramanian, B. & Ramachandran, S. (2008) 'Morphological changes at Vellar estuary, India—Impact of the December 2004 tsunami'. *Journal of environmental management*, 89 (1). pp 45-57.

Parsons, D. R., Schindler, R. J., Hope, J. A., Malarkey, J., Baas, J. H., Peakall, J., Manning, A. J., Ye, L., Simmons, S. & Paterson, D. M. (2016) 'The role of biophysical cohesion on subaqueous bed form size'. *Geophysical research letters*,

Paul, F., Huggel, C. & Kääb, A. (2004) 'Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers'. *Remote Sensing of Environment*, 89 (4). pp 510-518.

Pérez-Ruzafa, Á., Marcos, C. & Pérez-Ruzafa, I. (2012) 'Recent advances in coastal lagoons ecology: evolving old ideas and assumptions'. *Transitional Waters Bulletin*, 5 (1). pp 50-74.

Pérez-Ruzafa, A., Mompeán, M. C. & Marcos, C. (2007) 'Hydrographic, geomorphologic and fish assemblage relationships in coastal lagoons'. *Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues.* Springer, pp 107-125.

Perillo, G. M. (1995) 'Definitions and geomorphologic classifications of estuaries'. *Geomorphology and sedimentology of estuaries. Developments in Sedimentology*, 53 pp 17-47.

Pethick, J. (1993) 'Shoreline adjustments and coastal management: physical and biological processes under accelerated sea-level rise'. *Geographical Journal*, pp 162-168.

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J. & Stenseth, N. C. (2005) 'Using the satellite-derived NDVI to assess ecological responses to environmental change'. *Trends in Ecology & Evolution*, 20 (9).pp 503-510.

Phillips Olusegun, A., Falana Adenike, O. & Olayiwola Moshood, A. (2012) 'Assessment of environmental impact on benthic foraminiferal distribution in Lagos Lagoon, Nigeria'. *Journal of Mining and Geology*, 48 (1). pp 68-78.

Phleger, F. (1981) 'A review of some general features of coastal lagoons'. *UNESCO Technical Papers in Marine Science.*

Phlips, E., Badylak, S. & Grosskopf, T. (2002) 'Factors affecting the abundance of phytoplankton in a restricted subtropical lagoon, the Indian River Lagoon, Florida, USA'. *Estuarine, Coastal and Shelf Science*, 55 (3). pp 385-402.

Piazena, H. & Häder, D. P. (1994) 'Penetration of solar UV irradiation in coastal lagoons of the southern Baltic Sea and its effect on phytoplankton communities'. *Photochemistry and photobiology*, 60 (5). pp 463-469.

Picado, A., Dias, J. M. & Fortunato, A. B. (2010) 'Tidal changes in estuarine systems induced by local geomorphologic modifications'. *Continental Shelf Research*, 30 (17). pp 1854-1864.

Pilgrim, D., Chapman, T. & Doran, D. (1988) 'Problems of rainfall-runoff modelling in arid and semiarid regions'. *Hydrological Sciences Journal*, 33 (4). pp 379-400.

Pitts, P. A. (1989) 'Upwind return flow in a coastal lagoon: seasonal-scale barotropic transport'. *Estuaries*, 12 (2). pp 92-97.

Poppe, L. J., Eliason, A. H. & Hastings, M. (2004) 'A Visual Basic program to generate sediment grain-size statistics and to extrapolate particle distributions'

Potter, I. C., Chuwen, B. M., Hoeksema, S. D. & Elliott, M. (2010) 'The concept of an estuary: a definition that incorporates systems which can become closed to the ocean and hypersaline'. *Estuarine, Coastal and Shelf Science*, 87 (3). pp 497-500.

Prandle, D. (2009) *Estuaries: Dynamics, Mixing, Sedimentation and Morphology.* First paperback edn. Edinburgh, United Kingdom: Cambridge : Cambridge University Press.

Pritchard, D. W. (1952) 'Salinity distribution and circulation in the Chesapeake Bay estuarine system'. *Journal of Marine Research*, 11 (2). pp 106-123.

Pritchard, D. W. (1967) 'What is an estuary: physical viewpoint'. *Estuaries*, 83 pp 3-5.

Pugh, D. T. (1996) Tides, surges and mean sea-level (reprinted with corrections). John Wiley & Sons Ltd.

Rahmstorf, S. (2007) 'A semi-empirical approach to projecting future sea-level rise'. *Science*, 315 (5810). pp 368-370.

Ramsey, M. & Gillespie, A. (2012) 'Is emissivity immutable?', *AGU Fall Meeting Abstracts*. pp. 2765.

Ranasinghe, R., Pattiaratchi, C. & Masselink, G. (1999) 'A morphodynamic model to simulate the seasonal closure of tidal inlets'. *Coastal Engineering*, 37 (1). pp 1-36.

Raup, B., Kääb, A., Kargel, J. S., Bishop, M. P., Hamilton, G., Lee, E., Paul, F., Rau, F., Soltesz, D. & Khalsa, S. J. S. (2007) 'Remote sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) project'. *Computers & Geosciences*, 33 (1). pp 104-125.

Richards, J. A. & Richards, J. (1999) *Remote sensing digital image analysis.* vol. 3. Springer.

Ridderinkhof, H. & Zimmerman, J. (1992) 'Chaotic stirring in a tidal system'. *Science*, 258 (5085). pp 1107-1111.

Rippeth, T. & Simpson, J. (1996) 'The frequency and duration of episodes of complete vertical mixing in the Clyde Sea'. *Continental Shelf Research*, 16 (7). pp 933-947.

Rochette, J. (2009) 'Challenge, dialogue, action… Recent developments in the protection of coastal zones in Italy'. *Journal of Coastal Conservation*, 13 (2-3). pp 131-139.

Roelvink, J. (2006) 'Coastal morphodynamic evolution techniques'. *Coastal Engineering*, 53 (2). pp 277-287.

Roelvink, J., Walstra, D. & Chen, Z. (1994) 'Morphological modelling of Keta lagoon case'. *Coastal Engineering Proceedings*, 1 (24).

Roselli, L., Fabbrocini, A., Manzo, C. & D'Adamo, R. (2009) 'Hydrological heterogeneity, nutrient dynamics and water quality of a non-tidal lentic ecosystem (Lesina Lagoon, Italy)'. *Estuarine, Coastal and Shelf Science*, 84 (4). pp 539-552.

Roy, P., Williams, R., Jones, A., Yassini, I., Gibbs, P., Coates, B., West, R., Scanes, P., Hudson, J. & Nichol, S. (2001) 'Structure and function of south-east Australian estuaries'. *Estuarine, Coastal and Shelf Science*, 53 (3). pp 351-384.

Ruiz-Luna, A. & Berlanga-Robles, C. A. (2003) 'Land use, land cover changes and coastal lagoon surface reduction associated with urban growth in northwest Mexico'. *Landscape Ecology*, 18 (2). pp 159-171.

Ruiz-Luna, A. & Berlanga-Robles, C. A. (2003) 'Land use, land cover changes and coastal lagoon surface reduction associated with urban growth in north-west Mexico'. *Landscape Ecology*, 18 (2).pp 159-171.

Saito, K., Spence, R. J., Going, C. & Markus, M. (2004) 'Using high-resolution satellite images for post-earthquake building damage assessment: a study following the 26 January 2001 Gujarat earthquake'. *Earthquake Spectra*, 20 (1).pp 145-169.

Salvati, L. & Sabbi, A. (2011) 'Exploring long-term land cover changes in an urban region of southern Europe'. *International Journal of Sustainable Development & World Ecology*, 18 (4).pp 273-282.

Salvati, L. & Zitti, M. (2012) 'Monitoring vegetation and land use quality along the rural–urban gradient in a Mediterranean region'. *Applied Geography*, 32 (2).pp 896-903.

Salvati, L., Munafo, M., Morelli, V. G. & Sabbi, A. (2012) 'Low-density settlements and land use changes in a Mediterranean urban region'. *Landscape and Urban Planning*, 105 (1).pp 43-52.

Sanchez-Arcilla, A. & Jimenez, J. A. (1997) 'Physical impacts of climatic change on deltaic coastal systems (I): an approach'. *Climatic Change*, 35 (1). pp 71-93.

Sánchez-Arcilla, A., Jiménez, J. A., Valdemoro, H. I. & Gracia, V. (2008) 'Implications of climatic change on Spanish Mediterranean low-lying coasts: The Ebro delta case'. *Journal of Coastal Research*, pp 306-316.

Sánchez-Arcilla, A., Jiménez, J., Stive, M., Ibañez, C., Pratt, N., Day, J. & Capobianco, M. (1996) 'Impacts of sea-level rise on the Ebro Delta: a first approach'. *Ocean & Coastal Management*, 30 (2). pp 197-216.

Savenije, H. H. G. (1992) *Rapid assessment technique for salt intrusion in alluvial estuaries*. TU Delft, Delft University of Technology.

Scherner, F., Horta, P. A., de Oliveira, E. C., Simonassi, J. C., Hall-Spencer, J. M., Chow, F., Nunes, J. M. C. & Pereira, S. M. B. (2013) 'Coastal urbanization leads to remarkable seaweed species loss and community shifts along the SW Atlantic'. *Marine Pollution Bulletin*, 76 (1). pp 106-115.

Schmuller, J. (2013) *Statistical analysis with Excel for dummies.* John Wiley& Sons.

Schubel, J. (1971) 'Tidal variation of the size distribution of suspended sediment at a station in the Chesapeake Bay turbidity maximum'. *Netherlands Journal of Sea Research*, 5 (2). pp 252-266.

Seixas, C. S. (2002) *Social-ecological dynamics in management systems: investigating a coastal lagoon fishery in southern Brazil*. University of Manitoba.

Serra, P., Pons, X. & Saurí, D. (2008) 'Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors'. *Applied Geography*, 28 (3). pp 189-209.

Serrano, D., Ramírez-Félix, E. & Valle-Levinson, A. (2013) 'Tidal hydrodynamics in a two-inlet coastal lagoon in the Gulf of California'. *Continental Shelf Research*, 63 pp 1-12.

Sharma, K., Vangani, N., Menenti, M., Huygen, J. & Vich, A. (1994) 'Spatiotemporal variability of sediment transport in arid regions'. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences*, 224 pp 251-258.

Sheldon, J. E. & Alber, M. (2006) 'The calculation of estuarine turnover times using freshwater fraction and tidal prism models: a critical evaluation'. *Estuaries and Coasts*, 29 (1). pp 133-146.

Shields Jr, F. D., Simon, and A. & Steffen, L. J. (2000) Reservoir effects on downstream river channel migration. *Environmental Conservation,* 27 (01). pp 54-66.

Short, F. T. & Neckles, H. A. (1999) 'The effects of global climate change on seagrasses'. *Aquatic Botany*, 63 (3). pp 169-196.

Simas, T., Nunes, J. & Ferreira, J. (2001) 'Effects of global climate change on coastal salt marshes'. *Ecological Modelling*, 139 (1). pp 1-15.

Sinha, S. K., Dewangan, P. & Sain, K. (2016) 'Estimation of sea surface temperature (SST) using marine seismic data'. *Pure and Applied Geophysics*, 173 (4). pp 1305-1316.

Small, C. & Nicholls, R. J. (2003) 'A global analysis of human settlement in coastal zones'. *Journal of Coastal Research*, pp 584-599.

Smith, H. D., Ballinger, R. C. & Stojanovic, T. A. (2012) 'The spatial development basis of marine spatial planning in the United Kingdom'. *Journal of Environmental Policy & Planning*, 14 (1). pp 29-47.

Smith, H. D., Maes, F., Stojanovic, T. A. & Ballinger, R. C. (2011) 'The integration of land and marine spatial planning'. *Journal of Coastal Conservation*, 15 (2). pp 291-303.

Smith, N. P. (1978) 'Long-period, estuarine-shelf exchanges in response to meteorological forcing'. *Elsevier Oceanography Series*, 23 pp 147-159.

Smith, S., Crossland, J. M. & Crossland, C. (1999) *Mexican and Central American coastal lagoon systems: carbon, nitrogen and phosphorus fluxes (regional workshop II).* LOICZ International Project Office, Netherlands Institute for Sea Research.

Snyder, W. C., Wan, Z., Zhang, Y. & Feng, Y.-Z. (1998) 'Classification-based emissivity for land surface temperature measurement from space'. *International Journal of Remote Sensing*, 19 (14). pp 2753-2774.

Sobrino, J. A., Jiménez-Muñoz, J. C. & Paolini, L. (2004) 'Land surface temperature retrieval from LANDSAT TM 5'. *Remote Sensing of Environment*, 90 (4). pp 434-440.

Sohn, G. & Dowman, I. (2001) 'Extraction of buildings from high-resolution satellite data'. *Automated Extraction of Man-Made Objects from Aerial and Space Images (III). Balkema Publishers, Lisse*, pp 345-355.

Soons, J., Shulmeister, J. & Holt, S. (1997) 'The Holocene evolution of a well nourished gravelly barrier and lagoon complex, Kaitorete “Spit”, Canterbury, New Zealand'. *Marine Geology*, 138 (1). pp 69-90.

Soulsby, R.L., Manning, A.J., Spearman, J., Whitehouse, R.J.S. (2013). Settling velocity and mass settling flux of flocculated estuarine sediments. Marine Geology doi.org/10.1016/j.margeo.2013.04.006.

Spearman, J. R. and Manning, A.J. (*in press*). Hindered settling: a discussion. Ocean Dynamics.

Stanica, A. & Ungureanu, V. G. (2010) 'Understading coastal morphology and sedimentology'. *Terre Et Environment*, 88 pp 105 - 111.

Stanley, D. J. & Warne, A. G. (1993) 'Nile Delta: recent geological evolution and human impact'. *Science*, 260 (5108). pp 628-634.

Stauble, D. K., Garcia, A. W., Kraus, N. C., Grosskopf, W. G. & Bass, G. P. (1993) *Beach nourishment project response and design evaluation: Ocean City, Maryland.* DTIC Document. Available.

Stedmon, C. A., Markager, S. & Kaas, H. (2000) 'Optical properties and signatures of chromophoric dissolved organic matter (CDOM) in Danish coastal waters'. *Estuarine, Coastal and Shelf Science*, 51 (2). pp 267-278.

Stive, M. J. (2003) 'Advances in morphodynamics of coasts and lagoons', *Int. Conf. Estuaries Coasts, Hangzhou, China*. Zhejiang University Press.

Stokes, G.G., 1851. On the effect of the internal friction on the motion of pendulums, *Transactions of the Cambridge Philosophical Society*, 9, 8-106.

Su, J. & Chen, W. (1992) 'On meteorologically induced subtidal motions in Hangzhou Bay'. *Dynamics and exchanges in estuaries and the coastal zone*, pp 173-190.

Sun, D. & Kafatos, M. (2007) 'Note on the NDVI-LST relationship and the use of temperature-related drought indices over North America'. *Geophysical research letters*, 34 (24).

Sun, C., Xu, J., Liu, Z., Tong, M. & Zhu, B. (2008) 'Application of Argo Data in the Analysis of Water Masses in the Northwest Pacific Ocean'. *Marine Science Bulletin*, 10 (2). pp 13.

Sunday, O. A. & Ajewole, A. I. (2006) 'Implications of the changing pattern of landcover of the Lagos Coastal Area of Nigeria'. *American-Eurasian Journal of Scientific Research*, 1 (1).pp 31-37.

Swerpel, S. & Warszawy, P. (1987) 'Temperature and salinity of surface water at coastal measuring point, Isbiornhamna, Spitsbergen'. *Polish Polar Research*, 8 (1). pp 57-64.

Taiwo, O. J. & Areola, O. (2009) 'A spatial-temporal analysis of wetland losses in the Lagos coastal region, southwestern Nigeria, using multi-date satellite imagery', *2009 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, pp. III-928-III-930.

Takeoka, H. (1984) 'Fundamental concepts of exchange and transport time scales in a coastal sea'. *Continental Shelf Research*, 3 (3). pp 311-326.

Tambroni, N., Ferrarin, C. & Canestrelli, A. (2010) 'Benchmark on the numerical simulations of the hydrodynamic and morphodynamic evolution of tidal channels and tidal inlets'. *Continental Shelf Research*, 30 (8). pp 963-983.

Thieler, E. R. & Hammar-Klose, E. S. (1999) National assessment of coastal vulnerability to sea-level rise; US Atlantic Coast. (Report No. 2331-1258).

Thom, R., Williams, G. & Diefenderfer, H. (2005) 'Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment: is net ecosystem improvement possible?' *Restoration Ecology*, 13 (1). pp 193-203.

Thome, K. (2001) 'Absolute radiometric calibration of Landsat 7 ETM+ using the reflectance-based method'. *Remote Sensing of Environment*, 78 (1). pp 27-38.

Titus, J. G. & Anderson, K. E. (2009) Coastal sensitivity to sea level rise: a focus on the mid Atlantic Region. Government Printing Office.

Titus, J. G., Hudgens, D., Trescott, D., Craghan, M., Nuckols, W., Hershner, C., Kassakian, J., Linn, C., Merritt, P. & McCue, T. (2009) 'State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast'. *Environmental Research Letters*, 4 (4). pp 044008.

Titus, J. G., Park, R. A., Leatherman, S. P., Weggel, J. R., Greene, M. S., Mausel, P. W., Brown, S., Gaunt, C., Trehan, M. & Yohe, G. (1991) 'Greenhouse effect and sea level rise: the cost of holding back the sea'. *Coastal Management*, 19 (2). pp 171-204.

Townshend, J. R., Masek, J. G., Huang, C., Vermote, E. F., Gao, F., Channan, S., Sexton, J. O., Feng, M., Narasimhan, R. & Kim, D. (2012) 'Global characterization and monitoring of forest cover using Landsat data: opportunities and challenges'. *International Journal of Digital Earth*, 5 (5). pp 373-397.

Tufte, E. R. & Graves-Morris, P. (1983) *The visual display of quantitative information.* vol. 2. Graphics press Cheshire, CT.

Tyler, A. C. & Zieman, J. C. (1999) 'Patterns of development in the creekbank region of a barrier island Spartina alterniflora marsh'. *Marine Ecology Progress Series*, 180 pp 161-177.

Uduma-Olugu, N. & Adebamowo, M. (2015) 'Nature, tourism and landscape assessment of the Lagos Lagoon waterfront'. *WIT Transactions on The Built Environment*, 148 pp 149-161.

UKHO (2013) 'United Kingdom Hydrographic Office'. [Online]. Available at: www.ukho.gov.uk (Accessed: 12th June 2013).

Umgiesser, G. & Zonta, R. (2010) 'Classification and physical attributes of wetlands and their interaction with pollutant inputs'. *Terre Et Environment*, 88 pp 79-87.

Umgiesser, G., Sclavo, M., Carniel, S. & Bergamasco, A. (2004) 'Exploring the bottom stress variability in the Venice Lagoon'. *Journal of Marine Systems*, 51 (1). pp 161-178.

USACoE, (1994) 'Hydrographic surveying. Engineer Manual EM 1110-2-1003'. US Army Corps of Engineers, Washington, DC, Van Der Wal, D. & Pye, K. (2003) 'The use of historical bathymetric charts in a GIS to assess morphological change in estuaries'. *The Geographical Journal*, 169 (1).pp 21-31.

Van Lancker, V., Lanckneus, J., Hearn, S., Hoekstra, P., Levoy, F., Miles, J., Moerkerke, G., Monfort, O. & Whitehouse, R. (2004) 'Coastal and nearshore morphology, bedforms and sediment transport pathways at Teignmouth (UK)'. *Continental Shelf Research*, 24 (11). pp 1171-1202.

VAN Os, A. G., 1990. 'Density Currents and Salt Intrusion'. *Lecture Note for the Hydraulic Engineering Course at IHE-Delft Hydraulics*, Delft, Netherlands.

Vaz, N., Dias, J. M. & Leitão, P. C. (2009) 'Three-dimensional modelling of a tidal channel: the Espinheiro Channel (Portugal)'. *Continental Shelf Research*, 29 (1). pp 29-41.

Vaz, N., Fernandes, L., Leitão, P., Dias, J. & Neves, R. (2009) 'The Tagus estuarine plume induced by wind and river runoff: Winter 2007 case study'. *Journal of Coastal Research*, pp 1090-1094.

Venayagamoorthy, S. K. & Koseff, J. R. (2016) 'On the flux Richardson number in stably stratified turbulence'. *Journal of Fluid Mechanics*, 798 pp R1..

Vitousek, P. M., Mooney, H. A., Lubchenco, J. & Melillo, J. M. (1997) 'Human domination of Earth's ecosystems'. *Science*, 277 (5325). pp 494-499.

Wald, L., Ranchin, T. & Mangolini, M. (1997) 'Fusion of satellite images of different spatial resolutions: assessing the quality of resulting images'. *Photogrammetric engineering and remote sensing*, 63 (6).pp 691-699.

Watson, E. B., Pasternack, G. B., Gray, A. B., Goñi, M. & Woolfolk, A. M. (2013) 'Particle size characterization of historic sediment deposition from a closed estuarine lagoon, Central California'. *Estuarine, Coastal and Shelf Science*, 126 pp 23-33.

Waycott, M., Duarte, C. M., Carruthers, T. J., Orth, R. J., Dennison, W. C., Olyarnik, S., Calladine, A., Fourqurean, J. W., Heck, K. L. & Hughes, A. R. (2009) 'Accelerating loss of seagrasses across the globe threatens coastal ecosystems'. *Proceedings of the National Academy of Sciences*, 106 (30). pp 12377-12381.

Weisberg, R. H. (1976) 'The Noutidal Flow in the Providence River of Narragansett Bay: A Stochastic Approach to Estuarine Circulation'. *Journal of Physical Oceanography*, 6 (5). pp 721-734.

Weng, Q., Lu, D. & Schubring, J. (2004) 'Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies'. *Remote Sensing of Environment*, 89 (4).pp 467-483.

Williams, D. L., Goward, S. & Arvidson, T. (2006) 'Landsat'. *Photogrammetric Engineering & Remote Sensing*, 72 (10). pp 1171-1178.

Wilson, J. S., Clay, M., Martin, E., Stuckey, D. & Vedder-Risch, K. (2003) 'Evaluating environmental influences of zoning in urban ecosystems with remote sensing'. *Remote Sensing of Environment*, 86 (3). pp 303-321.

Winterwerp, J. (2002) 'On the flocculation and settling velocity of estuarine mud'. *Continental Shelf Research*, 22 (9). pp 1339-1360.

Wolanski, E. (1986) 'An evaporation-driven salinity maximum zone in Australian tropical estuaries'. *Estuarine, Coastal and Shelf Science*, 22 (4). pp 415-424.

Wong, G. S. & Zhu, S. m. (1995) 'Speed of sound in seawater as a function of salinity, temperature, and pressure'. *The Journal of the Acoustical Society of America*, 97 (3). pp 1732-1736.

Woodcock, C. E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S. N., Helder, D. & Helmer, E. (2008) 'Free access to Landsat imagery'. *Science (New York, NY)*, 320 (5879). pp 1011.

Woodroffe, C. D. (2002) *Coasts: form, process and evolution.* Cambridge University Press.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B., Lotze, H. K., Micheli, F. & Palumbi, S. R. (2006) 'Impacts of biodiversity loss on ocean ecosystem services'. *Science*, 314 (5800). pp 787-790.

Wulder, M. A., White, J. C., Goward, S. N., Masek, J. G., Irons, J. R., Herold, M., Cohen, W. B., Loveland, T. R. & Woodcock, C. E. (2008) 'Landsat continuity: Issues and opportunities for land cover monitoring'. *Remote Sensing of Environment*, 112 (3). pp 955-969.

Xie, Y., Yu, M., Bai, Y. & Xing, X. (2006) 'Ecological analysis of an emerging urban landscape pattern—desakota: a case study in Suzhou, China'. *Landscape Ecology*, 21 (8). pp 1297-1309.

Yang, L., Huang, C., Homer, C. G., Wylie, B. K. & Coan, M. J. (2003) 'An approach for mapping large-area impervious surfaces: synergistic use of Landsat7 ETM+ and high spatial resolution imagery'. *Canadian Journal of Remote Sensing*, 29 (2).pp 230-240.

Yu, Q., Gong, P., Clinton, N., Biging, G., Kelly, M. & Schirokauer, D. (2006) 'Object-based detailed vegetation classification with airborne high spatial resolution remote sensing imagery'. *Photogrammetric Engineering & Remote Sensing*, 72 (7).pp 799-811.

Yuan, F. & Bauer, M. E. (2007) 'Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery'. *Remote Sensing of Environment*, 106 (3). pp 375-386.

Yue, W., Xu, J., Tan, W. & Xu, L. (2007) 'The relationship between land surface temperature and NDVI with remote sensing: application to Shanghai Landsat 7 ETM+ data'. *International Journal of Remote Sensing*, 28 (15).pp 3205-3226.

Zhu, D., Feng, K. & Schelly, Z. (1992) 'Reverse micelles of Triton X-100 in cyclohexane: effects of temperature, water content, and salinity on the aggregation behavior'. *The Journal of Physical Chemistry*, 96 (5). pp 2382-2385.

Appendices

Appendix 1

This section of appendix contains results of Andreasen experiment that was performed on the water sample collected at various locations on the Lagoon. The experiment was carried out in order to investigate the Particle Size Distribution (PSD) across the area covered on the Lagoon during this study. The coordinates of the locations where the samples were collected are indicated on each of the Tables and Figures below. It also includes a Wentworth Grain Size chart for the purpose of defining size range of particles from the Lagoon.

Table 6-A1: Andreasen empirical test on the sample data at the Outlet (542329mE, 714581mN,)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (μm)
0	1	7.55	8.04	0.54	100	-
0.5	2	7.55	8.08	0.53	98.15	76.59
1	3	7.55	8.06	0.51	94.44	54.15
3	4	7.52	8.02	0.50	92.59	31.27
5	5	6.97	7.46	0.49	90.74	24.22
10	6	9.60	10.08	0.48	88.89	17.13
20	7	7.02	7.49	0.47	87.04	12.11
30	8	7.04	7.51	0.47	87.04	9.89

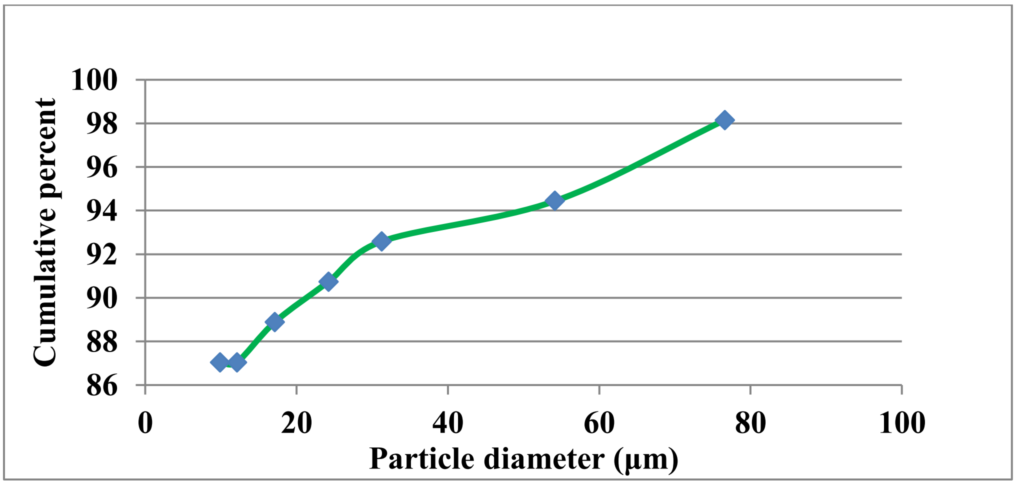


Figure 6-A1: Andreasen empirical test on the sample data at the Outlet (542329mE, 714581mN)

Table 6-A2: Andreasen empirical test on the sample data at the Ebute-Meta (542625mE, 715724mN)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (µm)
0	1	7.0	7.43	0.43	100	-
0.5	2	7.5	7.92	0.42	97.67	76.59
1	3	7.6	7.96	0.40	93.02	54.16
3	4	7.6	8.00	0.39	90.7	31.27
5	5	7.0	7.47	0.36	83.72	24.22
10	6	7.6	8.02	0.32	74.42	17.13
20	7	7.6	8.02	0.30	69.77	12.11
30	8	7.0	7.48	0.28	65.11	9.89

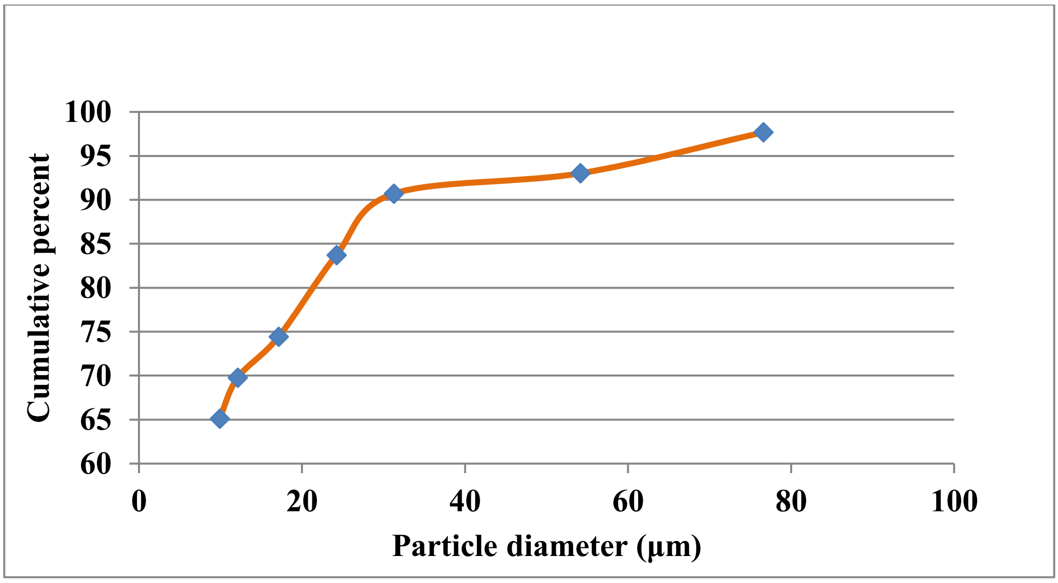


Figure 6-A2: Andreasen empirical test on the sample data at the Ebute-Meta (542625mE, 715724mN,)

Table 6-A3: Andreasen empirical test on the sample data at the Inlet (551320mE, 729480mN)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (µm)
0	1	7.52	7.78	0.26	100	-
0.5	2	7.56	7.82	0.26	98.08	77.52
1	3	7.55	7.80	0.25	96.92	54.82
3	4	7.56	7.80	0.24	93.46	31.65
5	5	7.53	7.77	0.24	90.38	24.52
10	6	7.54	7.77	0.23	88.46	17.33
20	7	7.55	7.78	0.23	86.53	12.26
30	8	7.54	7.72	0.22	85.38	10.01

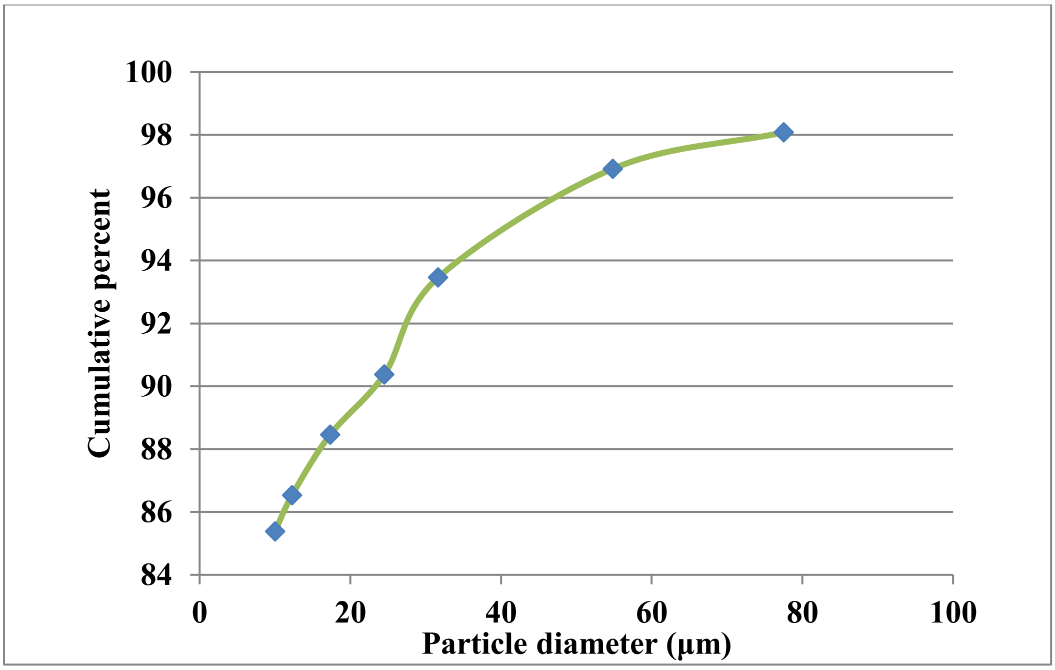


Figure 6-A3: Andreasen empirical test on the sample data at the Inlet (551320mE, 729480mN)

Table 6-A4: Andreasen empirical test on the sample data at the Mid-Region (550312mE, 717608mN)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (µm)
0	1	7.05	7.54	0.56	100	-
0.5	2	7.56	8.11	0.55	98.21	77.52
1	3	7.03	7.57	0.54	96.43	54.81
3	4	7.59	8.12	0.53	94.64	31.65
5	5	7.04	7.56	0.52	92.86	24.52
10	6	7.05	7.56	0.51	91.07	17.34
20	7	7.57	8.06	0.49	87.50	12.26
30	8	7.04	7.52	0.48	85.71	10.01

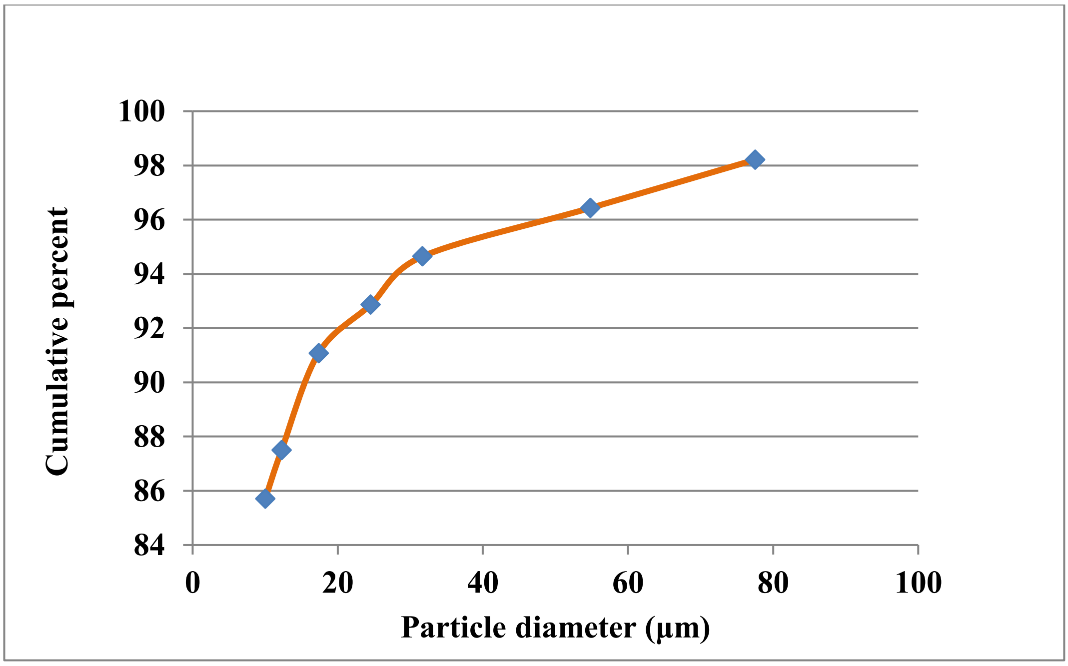


Figure 6-A4: Andreasen empirical test on the sample data at the Mid-Region (550312mE, 717608mN)

Table 6-A5: Andreasen empirical test on the sample data at Ijede (554950mE, 722533mN)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (µm)
0	1	7.55	7.87	0.32	100	-
0.5	2	7.53	7.82	0.29	92.06	76.6
1	3	7.56	7.84	0.28	88.89	54.16
3	4	7.54	7.82	0.28	87.3	31.27
5	5	6.99	7.26	0.27	85.71	24.22
10	6	9.61	9.87	0.26	83.49	17.12
20	7	7.03	7.27	0.24	74.6	12.11
30	8	7.01	7.23	0.22	71.11	9.89

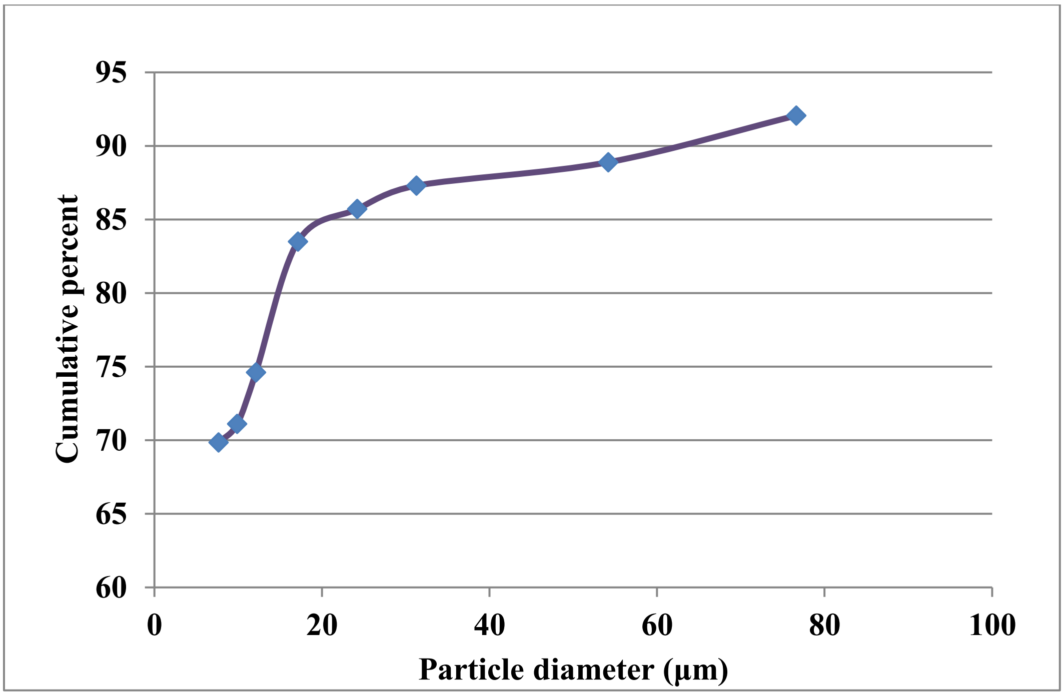


Figure 6-A5: Andreasen empirical test on the sample data at Ijede (554950mE, 722533mN)

Table 6-A6: Andreasen empirical test on the sample data at Egbin North (567190mE, 724679mN)

Time (min)	Dish No	Dish Weight =W_c (g)	Dish + Dry Sed. =W_d (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (µm)
0	1	7.12	7.15	0.13	100	-
0.5	2	7.56	7.67	0.11	84.61	77.52
1	3	7.17	7.27	0.1	76.92	54.82
3	4	7.56	7.65	0.09	69.23	31.65
5	5	7.04	7.12	0.08	61.53	24.51
10	6	7.02	7.09	0.07	53.85	17.34
20	7	7.51	7.57	0.06	46.15	12.26
30	8	7.58	7.63	0.05	46.15	10.01

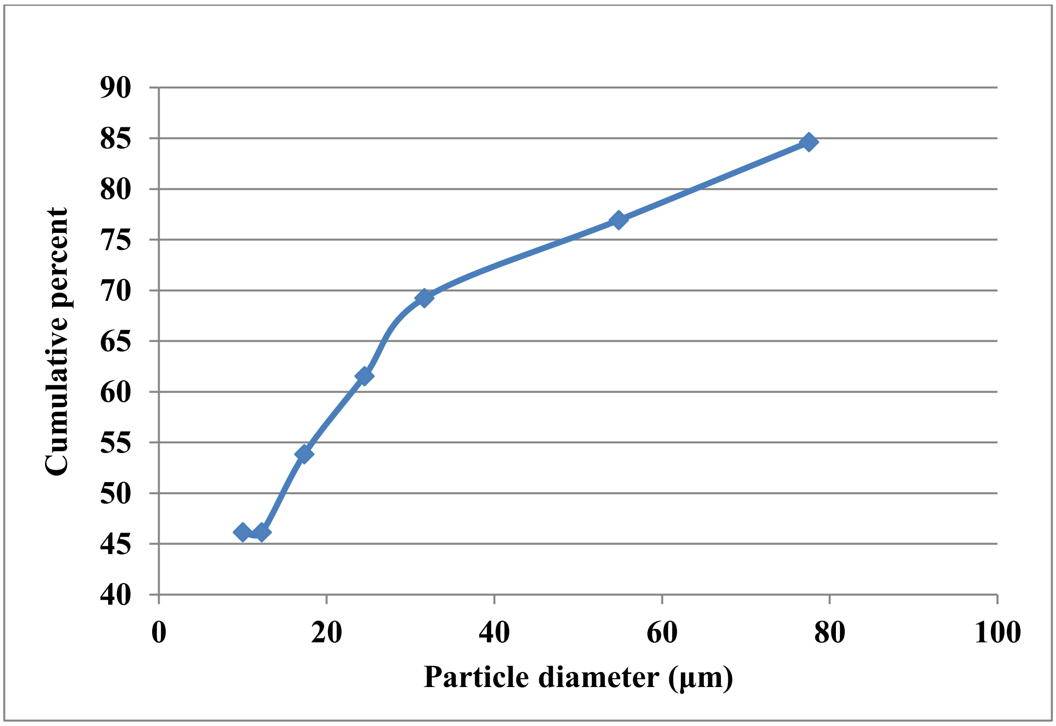


Figure 6-A6: Andreasen empirical test on the sample data at Egbin North (567190mE, 724679mN)

Table 6-A7: Andreasen empirical test on the sample data at Egbin South (564530mE, 720538mN)

Time (min)	Dish No	Dish Weight $=W_c$ (g)	Dish + Dry Sed. $=W_d$ (g))	Sed. Weight W_d-W_c (g)	Cummulative Weight (P) finer than d (%)	Particle Size d (μm)
0	1	7.12	7.15	0.13	100	-
0.5	2	7.56	7.67	0.11	84.61	77.52
1	3	7.17	7.27	0.1	76.92	54.82
3	4	7.56	7.65	0.09	69.23	31.65
5	5	7.04	7.12	0.08	61.53	24.51
10	6	7.02	7.09	0.07	53.85	17.34
20	7	7.51	7.57	0.06	46.15	12.26
30	8	7.58	7.63	0.05	46.15	10.01

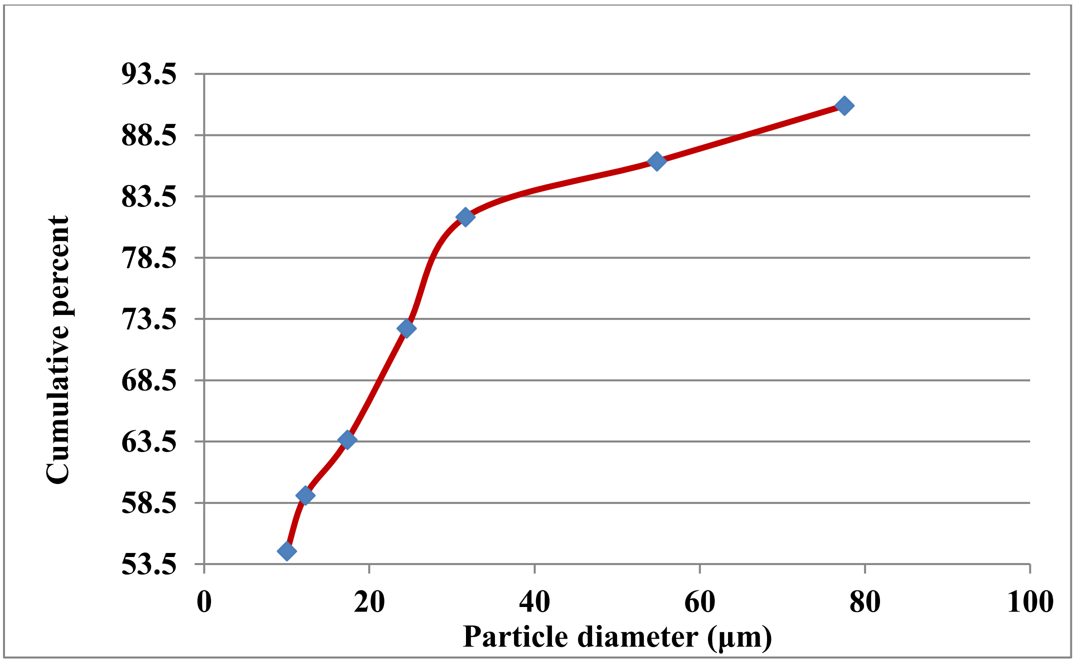
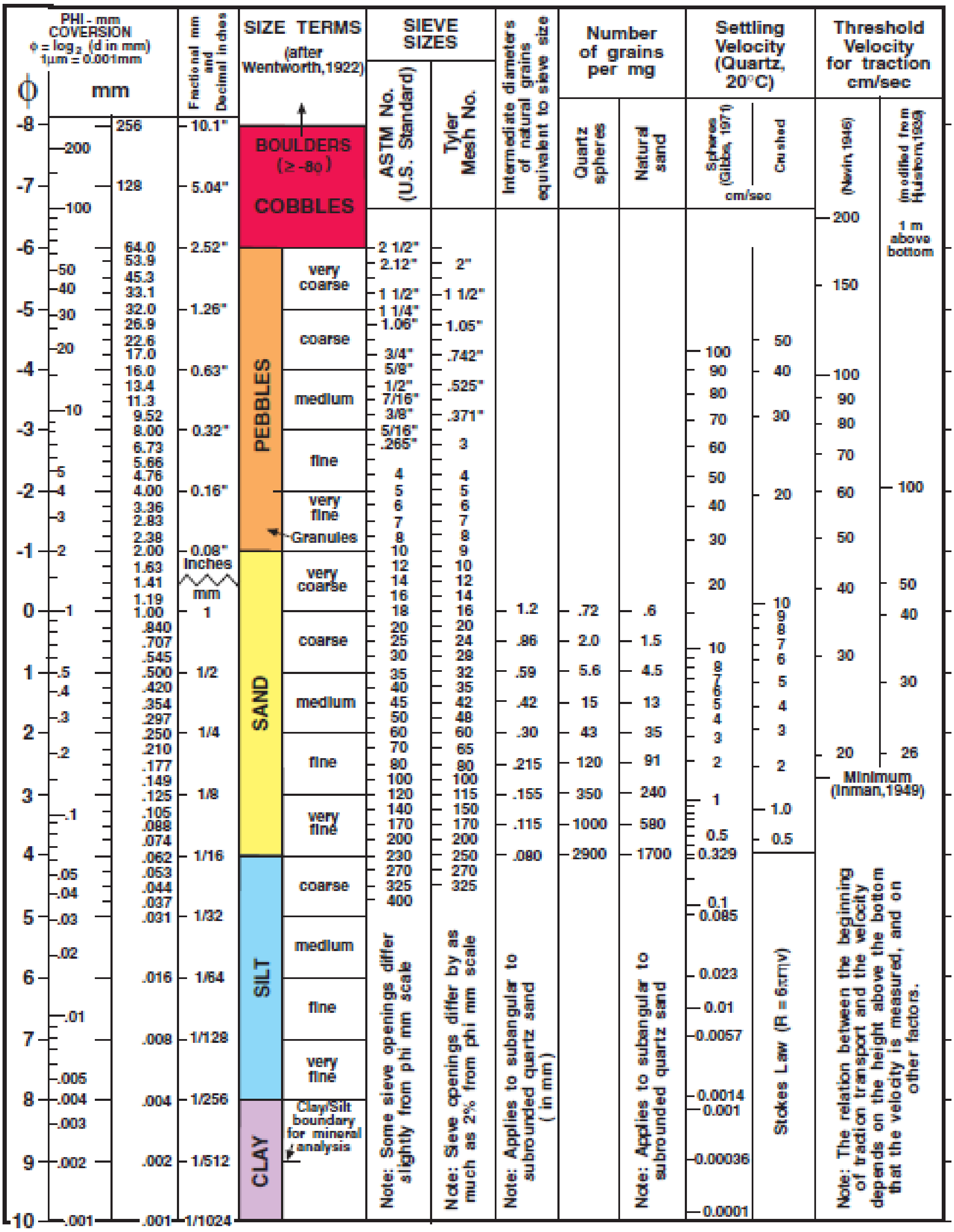


Figure 6-A7: Andreasen empirical test on the sample data at Egbin South (564530mE, 720538mN)

Table 6 – A7: Wentworth Grain Size Scale



Appendix 2

Appendix 2 shows few of the various photographs captured during the data collection in this study.

Fixing Valeport current meter for deployment into the Lagos Lagoon

Recovering Valeport current meter from the Lagoon after use

Collection of sediment sample from a location on the Lagoon with a locally made sediment corer

Lid of the locally made sediment corer was opened in order to collect sediment that are trapped inside the grabber so as to redploy it for collection of sediment in other location.

The corer about to be deployed for sediment collection in one of the location on the Lagoon

Dredger in one of the area subjected into dredging for the purpose of collecting sand for construction purpose in some sites within the Lagoon ecosystem

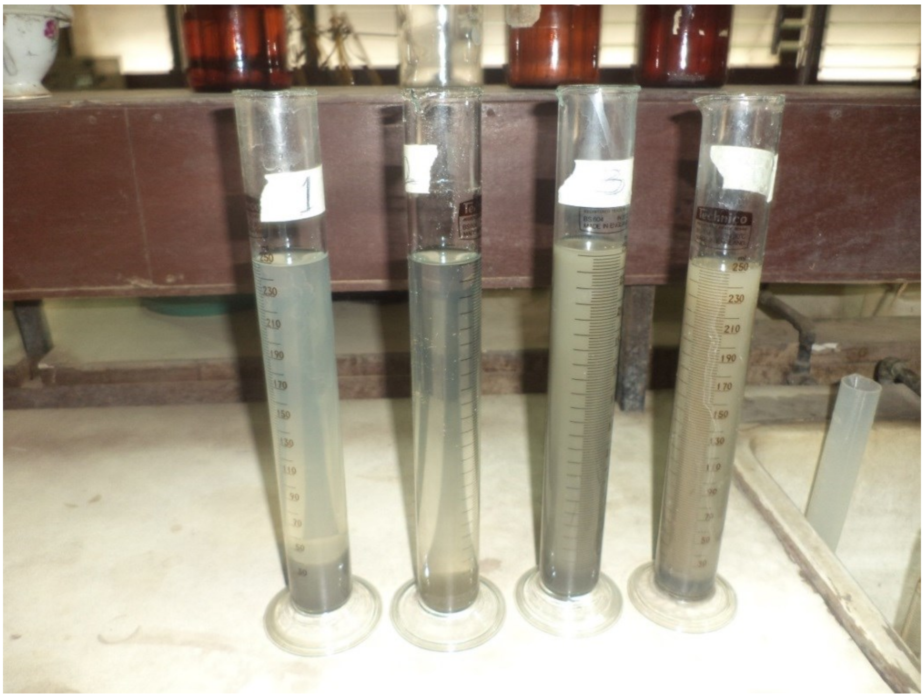


Figure showing the Hindered experiment, the tube contain sediment suspension that settles at different rate depending on the size of the particle. The experiment was carried out at the laboratory of the Department of Civil &Environmental Engineering, Faculty of Engineering, University of Lagos

The author putting some sediment samples inside an oven in the laboratory at the Department of Civil and Environmental Engineering, University of Lagos

The author while performing Andreasen Pipette experiment at the Department of Civil and Environmental Engineering, University of Lagos

The author while performing Andreasen Pipette experiment at the Department of Civil and Environmental Engineering, University of Lagos